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The use of waste and by-product materials to reduce cement content in paving blocks

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By

Ghassan Ab. Omran Jalull

May 2014

Coventry University

The work contained within this document has been submitted
by the student in partial fulfilment of the requirement of their course and award

The Use of Waste and By-Product Materials to Reduce Cement Content in Paving Blocks

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Ghassan Ab. Omran Jalull

May 2014

A thesis submitted in partial fulfilment of the University's requirements for the Degree of Doctor of Philosophy

Declaration

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements or within the text, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

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Date..

Conference Publication

1- Ghassan Jalull, Eshmaiel Ganjian and Homayoon Sadeghi-Pouya. (2012) "Reduction of cement in dry cementitious mix for paving blocks." Young Researchers' Forum in Construction Materials. Organised by SCI's Construction Materials Group. Congress Proceeding – PP 10-13. ISBN: 978-0-901001-36-8. Thursday 17 May, SCI HQ, London, UK.

2- Ghassan Jalull, Eshmaiel Ganjian and Homayoon Sadeghi-Pouya. (2013). "Reducing cement content in paving blocks by including basic oxygen slag." First Engineering Conference for Engineering Occupation. The Libyan Engineering Association Branch of Al Zawiya. Held 9-10 April, 2013. Al Zawiya, Libya.

3-Ganjian, E., Jalull, G., and Sadeghi-Pouya, H. (2013) "Low carbon foot print binders for paving blocks." Proceedings of the Third International Conference on Sustainable Construction Materials and Technologies, "Third International Conference on Sustainable Construction Materials and Technologies". Held Aug 2013 in Kyoto, Japan.

Journal Publication

1- Ghassan Jalull, Eshmaiel Ganjian, and Homayoon Sadeghi-Pouya. (2014) “Using GGBS with other mineral wastes to reduce cement in paving blocks”. ICE. Journal of Construction Materials. Volume 167. Issue CM2. Pages 91–103. ISSN: 1747-650X. UK.

2- Eshmaiel Ganjian, Ghassan Jalull and Homayoon Sadeghi-Pouya. (2014) “Reducing cement contents of paving blocks by using mineral waste and by-product materials”. ASCE. Journal of Materials in Civil Engineering. ISSN: 1943-5533. US.

3- Eshmaiel Ganjian, Ghassan Jalull and Homayoon Sadeghi-Pouya. (2014) “Using waste materials and by-products for green paving blocks”. ASCE. Journal of Materials in Civil Engineering. (Under review).

Other Publication

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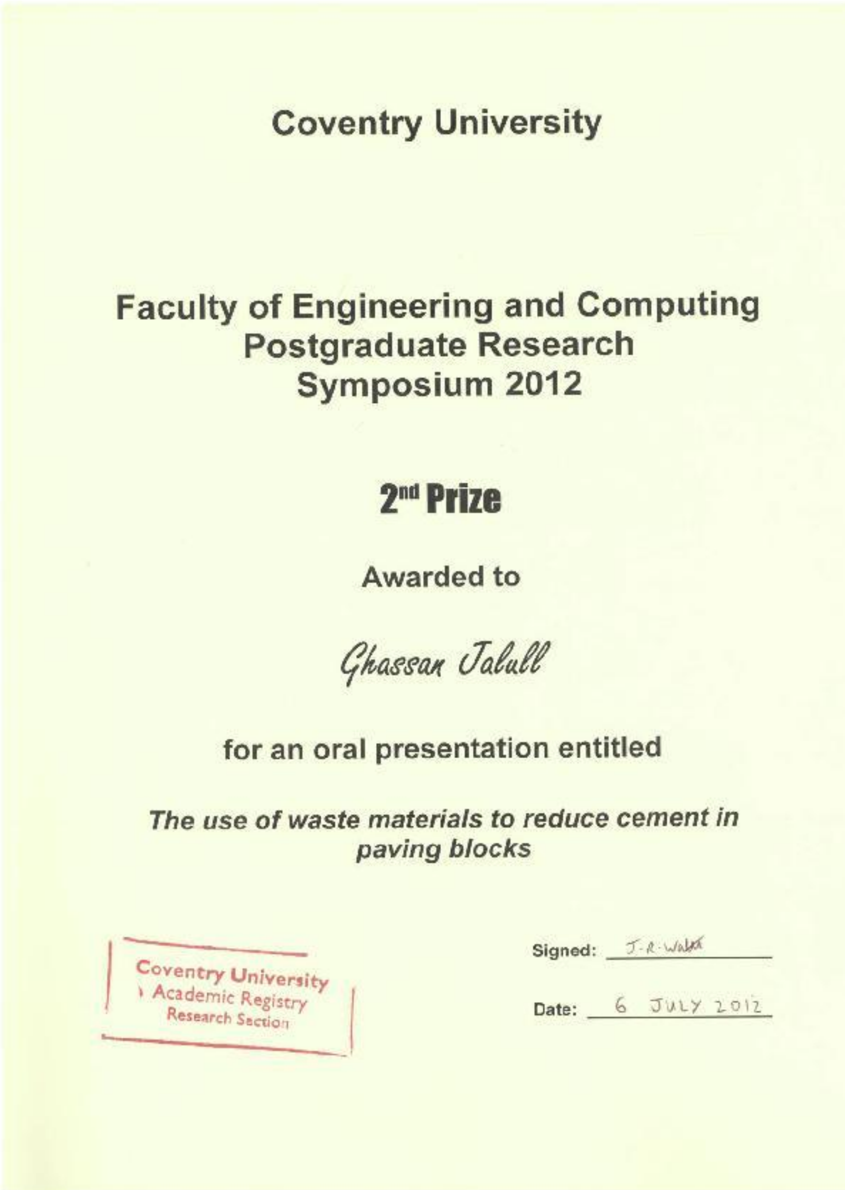
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Abstract

Paving blocks factories typically use at least 210 kg cement per m^3 to produce paving blocks. The production of Portland cement has significant adverse effects on the environment due to the emission of carbon dioxide. Therefore, reduction of Portland cement content will benefit the carbon footprint of concrete products.

The aim of this research was to reduce Portland cement in paving blocks production without having any adverse effects on the physical and durability characteristics. This research presented the use of non-hazard waste and by products materials such as ground granulated blast furnance slag (GGBS), basic oxygen slag (BOS), run-of-station ash (ROSA), plasterboard gypsum (PG), cement by-pass dust (BPD), incinerator bottom ash aggregate (IBAA), recycled crushed glass (RCG), recycled concrete aggregate (RCA), recycled bricks (RB), together with steel fibre (SF) and PVA-Fibre for the production of environmentally friendly paving blocks.

Paving blocks were produced by combinations of binary and ternary blends in ten different groups of mixes. The paving blocks were compacted using a hydraulic press to give similar compaction result to factory process. Paving blocks were tested for split tensile strength and compressive strength at 14 and 28 days, slip/skid resistance, weathering resistance, densities were also tested and measured. Furthermore XRD and XRF tests of selected mixes have been carried out. Data obtained from the ternary combinations were analyzed using response surface method and prediction models were created using MINITAB software.

Result of the ten binder mixes showed that BOS up to 70%, ROSA up to 60%, GGBS up to 45%, BPD up to 20%, and PG up to 5% by weight can replace the Portland cement without negative impacts on their desirable properties in accordance to the BS EN 1338: 2003. Moreover, concrete paving blocks prepared with OPC50-GGBS45-BPD5 (OPC7-GGBS6.3-BPD0.7) achieved reduction of cement content by up to 30% in comparison to the percentage currently being used in most factories, without having a substantial impact on the strength or durability of the paving blocks produced in accordance with BS EN 1338:2003. This reduction of cement content corresponds to using only 150 kg cement per m^3 for production of paving blocks.

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List of abbreviation

The following are the abbreviations which are used in this thesis

Ordinary Portland cement	OPC
Basic oxygen slag	BOS
Plasterboard gypsum	PG
Run-of-station ash	ROSA
Ground granulated blast furnace slag	GGBS
Cement by pass dust	BPD
Pulverised fuel ash	PFA
British pendulum number	BPN
Recycled concrete aggregate	RCA
Incinerator bottom ash aggregate	IBAA
Recycled crushed glass	RCG
Recycled bricks	RB
Steel wire Fibre	SF
Compressive strength	CS
Split tensile strength	TS
X-ray Fluorescence	XRF
X-Ray Diffraction test	XRD
Response Surface Method	RSM
Unpolished slip resistance value	USRV
Polished paver value	PPV

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1. Introduction

Concrete in the form of pre-cast paving blocks is widely used for a range of purposes including that of exterior landscaping for which such blocks are available in a number of shapes and colours. There has been a rapid expansion in the use of concrete paving blocks globally. In Europe, an annual 100 square feet ($\approx 9m^2$) of concrete paving blocks has been installed per person. However, in the US, only 1 square feet ($\approx 0.1m^2$) has been installed per person (Concrete network, 2014).

The appeal of paving blocks is that they are able to provide a hard surface which is visually attractive and easy to walk upon while at the same time allowing for easy maintenance and having a long life in use. They can therefore be used for the most heavy duty purposes, being able to cope with considerable loads as well as offering resistance to those forces that might shear the surface or otherwise damage it. Paving blocks can be used for a range of applications such as car parks, bus terminals and at bus stops as well as in petrol stations, on roundabouts, in industrial estates and many other uses.

Paving blocks of this type are fully engineered and factory produced, the blocks that are produced have a specific feature of interlocking capacity; which has a clear advantage compared with other types of surface. The final surface is produced by laying the blocks on a granular laying course which has an edge restraint so that the individual blocks will interlock with each other and function as a single surface able to cope with large point loads through an even distribution on such a surface. It is possible to use a paving blocks surface immediately after it has been laid and thereafter, throughout its useful and lengthy life, it will require only minimal maintenance.

Cement content is a very important issue in the production of paving blocks and it is usual for a minimum of 210 kg of cement per m^3 to be used. Researchers have investigated ways to reduce cement content in different construction products in order to reduce the environmental impacts of the products and to benefit in terms of the economic costs (Naik 2008).

When Portland cement is produced, it has a significant negative impact on the environment; this is due to the production of carbon dioxide emissions in production of Portland cement. Therefore, if it is possible to decrease the quantity of Portland cement and replace the content with other non carbon dioxide producing cementitious materials, the carbon footprint of concrete products will be significantly reduced without adversely affecting its durability and other physical characteristics.

This has become an urgent issue and it is necessary to look for suitable ways to solve this problem as soon as possible, in order to protect our environment, and encourage the use of waste materials to decrease the amount of Portland cement in civil engineering applications.

However, reduction of waste from industrial processes has become more complex and costly. On the other hand, there are stringent laws relating to the environment and a limit has been put on sites where waste can be disposed of. Therefore, government policies in all regions of the world are used to pro-actively promote the use of non-hazardous waste and by-products through construction regulations.

Nowadays, mineral additives are attracting a great deal of attention as materials that contribute to the improvement of specific properties of concrete, as well as decreasing the carbon dioxide emissions and energy generated in making the cement.

1.1 Aim and Objectives

The aim of this research is to explore the possibility of using a mixture of different non-hazardous waste materials to make paving blocks, and to reduce the percentage of Portland cement in the mixture. This should bring a reduction in CO_2 emission by reducing cement production; furthermore this should lead to reuse of waste materials in order to decrease their impact on the environment, specifically the problems from the disposal of waste materials to the landfill.

For this aim, the research objectives will be to:

- Develop cost-effective, novel cementitious mixes using a range of different non-hazardous waste and pozzolanic industrial by-product.
- Find the optimisation of mix proportion for the highest tensile strength.
- Reduce the percentage of OPC in the mixture as much as possible by use of non-hazardous waste materials to produce paving blocks.
- Replacing natural aggregates in the paving blocks with a range of demolition and construction waste materials.
- Finally this research will offer very important data to encourage factories to implement the findings in order to achieve green products.

2. Literature survey

Cement use dates back to ancient times. The ancient Egyptians used calcined impure gypsum, the Greeks and Romans utilized calcined limestone and through the years they learnt to add lime and water, sand and crushed stone or brick and broken tiles. This was the first concrete in history (Neville, 1995).

In the past, it was thought that cement and concrete did not date as far back; “most people believe that concrete has been in common use for many centuries, but this is not the case. The Romans did make use of cement called pozzolana before the birth of Christ. They found large deposits of a sandy volcanic ash near Mt. Vesuvius and in other places in Italy”. (McCormac and Nelson, 2006).

The Romans developed pozzolan-lime cement using volcanic ash (Van Oss. 2005), mixtures of ground pozzolan and lime were the basis of the cements used by the Romans, and can typically still be found in Roman structures that still stand; such as the Pantheon in Rome. Pozzolan-lime cement develops strength slowly, but its ultimate strength can be high. The hydration products found in pozzolan-lime cement that produces strength are essentially the same as those produced by Portland cement.

Pozzolan materials are not intrinsically cementitious, but when they are mixed with lime hydrated they form hydraulic cement as a result of their aluminosiliceous composition. The reaction of pozzolan with lime already existing in cement or liberated during the hydration process modifies some properties of the cements and the resulting concrete. (Mouli and Khelafi. 2008).

According to Ana and Paulo (2009) any pozzolanic material, whether its origin is natural or artificial, must have a high percentage of amorphous silica together with a high specific surface if it is to generate a pozzolanic reaction. Pozzolana is defined more appropriately by ASTM 618-94a as being a siliceous or siliceous and aluminous material that has no cementitious properties itself but in the presence of moisture, in a finely divided from, it will react chemically with calcium hydroxide at room temperate to form compounds possessing of cementitious properties.

There has been a recent increase in the re-use of waste materials with pozzolanic properties due to high demands resulting from the wide application of cementitious materials, and also because such materials are appropriate for a number of applications and have many clear advantages.

Cement is made by combining a homogeneous mixture of carefully proportioned raw materials (limestone or chalk and clay / shale and sand) at a very high temperature (145°C) in a rotary kiln. The raw materials fuse together to form 'clinker', a hard granular material. The clinker is ground into powder with gypsum to make cement.

The production of every tonne of Portland cement releases approximately 1 tonne of carbon dioxide - a major contributor to the greenhouse gas emissions that are responsible for global warming (Ghataora et al., 2004). Cement production accounts for roughly 8 % of global CO_2 emissions. (Olivier et al., 2012).

According to Turanli (2004) energy plays a very important part in the manufacture of Portland cement, “Portland cement manufacturing is an energy-intensive process in which approximately 4 GJ of energy/tonne, mostly obtained from the burning of fossil fuels, is consumed". Also by using more waste materials, their effect on the environment will be reduced and help to save natural raw materials as well as reducing the overall energy required producing a cementitious material. Thereby reducing the emissions of carbon dioxide (CO_2) (Ganjian et al. 2007).

Since 1970, attempts have been made to partially replace Portland cements with other materials in concrete. It was discovered that some types of pozzolans and limestones, which occur naturally, are possible alternatives to Portland cement. Other materials, such as Pulverised Fuel Ash and steel slag which are produced by various metallurgy processes are also possible alternatives (Menéndez et al., 2002; Al-Chaar et al., 2011; Courard et al. 2003; Li and Ding 2003).

The literature search done by the author confirmed that no cement replacement is used in paving blocks manufacturing except for GGBS and PFA which are used in some of the concrete paving blocks factories in UK. However, no researcher has been found to try to reduce the cement content of concrete paving blocks using other by-products or waste cementitious/pozzolanic materials. Other researchers have been using different recycled construction materials as a replacement for aggregate in paving blocks (Soutsos et al., 2011; Chan and Poon, 2006; Wattanasiriwech et al., 2009) but no cement binder replacement is investigated!

2.1 Uses of waste and by-products in the construction industry

Many types of industrial waste can be consumed in concrete either as a supplementary material or as a replacement of cement (or sand). Examples of industrial waste products are; coal pulverised fuel ash, ground granulated blast furnace slag, metakaolin, waste glass, plastics etc. These waste materials are very hard to discard and dispose correctly and can contribute to environmental problems; therefore the utilization of these waste products not only solves the disposal problems but also enhances concrete properties (Krishna and Sabnis, 2013).

Certain by-products can be sold to other industries to use or recycled during the steelmaking process; the uses of by-products maintain the sustainability of the steel industry. Other advantages of utilizing by-products are; reduced CO_2 emissions, prevention of landfill waste, preservation of natural resources and provides economical benefits when by-products are sold (World Steel Association, 2010).

In concrete products, many different types of waste and by-products are used as a replacement for cement, such as Pulverised Fuel Ash (PFA), run-of-station ash (ROSA), basic oxygen slag (BOS), ground granulated blast furnace slag (GGBS), cement by-pass dust (BPD), cement kiln dust (CKD), plasterboard gypsum (PG) and silica fume (SF). (Berryman et al., 2005; Ganjian et al., 2007; Konsta-Gdoutos et al., 2003).

There are two main types of waste and by-products used as replacement for cement, they are fuel ashes and steel slags.

2.1.1 Fuel ashes

2.1.1.1 Sources of ash

Thermal power plants produce electrical power by using coal, the process of combustion of pulverized coal produces large amounts of by-products. One of the by-products consists of Pulverised Fuel Ash and station ash. These ashes are divided so finely that they usually are even finer than cement. They are mainly comprised of glassy-spherical particles and also contain residue from hematite, magnetite and char, as well as some crystalline substances present as a result of the cooling process (Kokubu, 1969).

The physical and chemical properties of coal ash depend on the type, source, and fineness of the fuel as well as the operating conditions of the power plant.
Cyclone collectors and electronic precipitation bags are used to extract Pulverised Fuel Ash from the gases, it is then stored and ready for use (Churchill et al., 1999).

There are many environmental concerns regarding the use of Pulverised Fuel Ash, such as leaching and dusting. Pulverised Fuel Ash disposal is also a big concern, due to the large quantity of Pulverised Fuel Ash that must be disposed. Pulverised Fuel Ash has some great pozzolanic characteristics that are ideal for the construction industry. Therefore, using Pulverised Fuel Ash as a construction material not only replaces cement but also minimizes the problems occurred with Pulverised Fuel Ash disposal.

Pulverised Fuel Ash is divided into two different classes, it is separated depending on its chemical composition, fineness, and unburned carbon content, as stated by the standard ASTM C 618-03 2003. The two classes are class C and class F. Class C has no lime addition and high calcium content which makes it highly reactive with water, whereas class F contains a lower percentage of lime and is not as pozzolanic as type C. Another type of Pulverised Fuel Ash is known as run off station ash, this type of ash is collected from chimney stacks of powder stations, the ROSA is not classified or processed in any way and thus has no market value (Karami et al., 2012)

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2.1.1.2 Use of Pulverised fuel Ash

Pulverised Fuel Ash is used in concrete and is an inexpensive replacement for Portland cement, which when mixed with lime and water, forms a compound similar to Portland cement. The amount of Pulverised Fuel Ash used in the construction industry is increasing every year as a high percentage of cement in concrete can be replaced by Pulverised Fuel Ash. However, if a high percentage of Pulverised Fuel Ash is used to replace cement, it may result in the concrete having a low workability, which makes it unusable in the common manufacturing process (Berryman et al. 2005).

Pulverised Fuel Ash is a valuable mineral used in cement and concrete, as it improves the strength and ease of pumping concrete. In addition, it can also be used as an ingredient in bricks, paving blocks and structural fills. Jones and McCarthy (2005) found that using run of station ash in cement had a significantly beneficial effect on the strength of concrete at 28 days.

White (2006) investigated the stabilization of class C Pulverised Fuel Ash using calcium activators such as hydrated lime and cement kiln dust (CKD) in the construction of a structural pavement base layer. It was found that the strength and freeze-thaw durability of the stabilized mix increased with the use of calcium activators.

Ambarish and Chillara (2007) studied class F Pulverised Fuel Ash and modified with lime and gypsum content. The results of this study showed that adding up to 10% lime to class F Pulverised Fuel Ash improved the strength of the mixture. Adding 0.5%, 5% and 15% gypsum to lime modified the mix and caused the mix to gain higher strength in the early curing period. It was also found that if Pulverised Fuel Ash was stabilized with lime only, it required a longer curing period, such as 45 days or more to gain considerable shear strength.

2.1.2 Steel slags

2.1.2.1 Main types of slags

A brief description of the main types of slags is given below:

• **Basic oxygen slag (BOS)**

During the current production of steel it is inevitable that basic oxygen steel slag will be produced, for each tonne of steel produced, an estimated 300 kg basic oxygen steel slag is consequently produced (Moreno, 1999).

• **Ground granulated blast-furnace slag (GGBS)**

Ground granulated blast-furnace slag is produced by the extraction of pig iron from iron ore in a blast furnace. During the extraction, molten slag must be quenched sufficiently rapidly to form a glassy material, which when finely ground becomes ground granulated blast-furnace slag or GGBS.

2.1.2.2 Hydraulic activity of steel slag

The hydraulic activity of slag strongly depends on its chemical composition. The most significant variable and the most critical parameter to hyrdaulicity is the glass content of slag. The most important variable that affects the nature of slag is the temperature at which the furnace is tapped. One of the principal factors affecting slag cement strength is the glass content, this is affected by the rate of quenching and the slag samples with 30-65% glass content are suitable to show activation (Pal et al. 2003).

Ground granulated blast furnace slag can be made ‘active’ by mixing alkalis to the slag. The most economical alkali used is lime, although it is not a hydraulic substance on its own. This slag possesses properties that are similar to those of pozzolan lime cement. Granulated slag is the only type of slag that can be used effectively as a component of cement.

Basic oxygen slag is a well-known aggregate in civil engineering construction and road ballast. However, the existing free lime in basic oxygen slag causes a problem in its application in civil engineering projects. “The free lime of steel slag comes from two sources: residual free lime from the raw material and precipitated lime from molten slag” (Shi 2004). When free lime or limestone hydrates, its volume increases and swelling will occur (Reddy et al. 2006). To obtain stability, several methods have been employed, such as weathering of the slag outside in slag pits or treatment of liquid slag by injecting oxygen and silica or autoclaving slag in baskets (Reddy et al. 2006).

2.1.2.3 Uses of steel slag

Mahieux et al. (2008) conducted a study on the use of BOS in hydraulic road binders. BOS and GGBS were obtained from the same plant. The study found that although BOS in cement-based mortars had a poor hydraulic activity with no pozzolanic properties, the ternary blended binder mixing BOS, GGBS and catalyst was successful.

On the other hand, it was found that ground granulated blast furnace slag does not react with water at room temperature without an activator. Portland cement clinkers or lime is normally used as alkali activators (Heikal et al. 2002).

The use of blast furnace slag is preferred in the construction industry as it has a higher strength than conventional cements due to the use of proper alkaline activators. Ground steel slag also shows enhanced cementitious properties than regular cement when alkaline activators are used. (Shi, 2004).

Shih et al. (2004) found the potential of using waste steel slag in making bricks. It was found that if an appropriate amount of steel slag (less than 10%) was added to the mixture used (the slag content in the clay-slag mixture 10% by weight) to manufacture bricks, then the firing temperature is reduced. It was found that as the amount of slag increases, the compressive strength of this kind of brick and the shrinkage decreased. As slag content is increased water absorption also increases.

2.1.3 Cement by-pass dust

Cement by-pass dust (BPD) is a by-product of Portland cement production, when cement is produced cement by pass dust will also is produced. Cement by-pass dust is produced in the kiln by-pass. The by-pass cement dust is produced as solid waste during the manufacture of Portland cement clinker by using the dry process. Volatile constituents are also produced in the kiln feed; these constituents are not recycled back into the kiln feed. (Heikal et al. 2002).

2.1.3.1 Uses of cement by-pass dust

Taha et al. (2007) investigated the use of mixing cement by-pass dust with copper slag, incinerator ash, sand and cement to make controlled low strength materials (CLSMs). These are engineered materials that have a specified compressive strength between 0.1 MPa and 8.3 MPa at 28 days. CLSM has many uses, such as backfilling walls or trenches, bedding material for pipes, void fillings, sewers, tunnel shafts and some other underground structures.

2.1.3.1 Uses of cement by-pass dust

Taha et al.'s research (2007) implies that CLSM with suitable mechanical properties can be produced when the correct constituent materials are selected (e.g. using a good mix design). Another interesting finding of Taha et al.'s research was that mixes produced using a combination of waste material, cement and sand generated higher strength values than when waste materials were used alone to fully replace cement. Also, in order to improve pozzolanic activity, copper slag, incinerator ash and BPD should be combined with cement. Copper slag addition to the mix produced acceptable results, however, the performance is predicted to be vastly improved when copper slag fully replaces sand in CLSM; this is because copper slag has lower absorption and higher strength properties than sand (Taha et al. 2007).

2.2 The efficiency of producing paving blocks by using recycled construction and demolition wastes as aggregates

Across the world, substantial damage is being inflicted on the environment at a level which cannot be sustained as a result of high use of natural resources by the construction industry and the disposal of large quantities of waste that the industry produces as well as demolition waste. As a result, a significant number of governments globally are adopting active policies, so that both the use of primary resources will be increased and also to encourage an increase in reuse and recycling.

The potential use of industrial by-products and wastes being used in construction materials has gained vast attention in the past 25 years (Marikunte and Shah. 1993; Sobolev and Soboleva. 1997).

Waste construction materials recycling have many benefits such as; saves natural resources energy and reduces solid waste, air and water pollutants and greenhouse gases. The construction industry is only just starting to become aware of the vast potential and advantages utilizing waste and recycled materials can bring (Johnny et al., 2013).

Recycled materials have played a very important part in recent researches, in particular (Chan and Poon, 2006), demolition construction waste (Soutsos et al., 2011; Tempest et al., 2010), ceramic tile (Torkittikul and Chaipanich, 2010), crushed clay bricks (Chan and Poon, 2006; Padmini et al., 2001) and recycled concrete as aggregate replacement (Chan and Poon, 2006).

Converting recycled concrete and demolition waste into aggregate for use in new construction provides a way of increasing sustainability which benefits the environment while at the same time being economically attractive (Dhir et al., 1998).

Researchers have successfully shown that crushed construction and demolition waste as a recycled aggregate is possible for use in the construction industry (Tempest et al., 2010); this finding is also supported by practical experience in the industry.

Research has been carried out by Poon and Chan (2006) to produce paving blocks by using recycled concrete aggregate and crushed clay brick. Crushed clay brick is not considered to be a recyclable material in many countries compared with recycled concrete aggregate. The clay brick supplied from building, reconstruction and devastated places is mainly transferred to landfill or reclamation places for subtraction.

Poon and Dixon (2006) concluded that the uses of crushed clay brick decreased the density of the paving blocks and that the compressive and split tensile strengths of the paving blocks reduced as the content of crushed clay brick increased. In order to meet the minimum requirements of pedestrian areas, paving blocks consisted of 50% crushed clay brick and 50% recycled concrete aggregate. Paving blocks prepared with 25% crushed clay brick were also viable as long as they satisfied the compressive strength required for trafficked areas.

In the production of precast concrete paving blocks, the potential of using recycled aggregates was demonstrated by Tang et al., (2007). The study found that when 60%

of coarse natural aggregates were replaced with recycled masonry-derived aggregates in concrete paving blocks; the equivalent strength demands were still met without the need to increase cement content. Therefore, Tang et al's study (2007) recommends that 60% replacement of fine natural aggregates with concrete-derived aggregates produces paving blocks of a sufficient nature. The grading of natural and C&DW derived aggregates shown in Figure 2.1.

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Figure 2.1 : Sieve grading of natural and C&DW derived aggregates (Tang et al's study 2007).

It was confirmed by Poon et al. (2002), that when recycled aggregates replaced 25% and 50% of coarse and fine natural aggregates, there were minor impacts on the compressive strength of the blocks, but when there were higher levels of replacement by recycled aggregates, the compressive strength of the blocks decreased substantially. Furthermore, when up to 100% of recycled aggregates were used to replace natural aggregates, without the incorporation of Pulverised Fuel Ash, in concrete paving blocks, a compressive strength of 49 MPa or more was produced at 28 days. Whereas, Pulverised Fuel Ash can be incorporated into mixes for paving blocks with footway uses with compressive strengths of 30 MPa and lower. The blocks produced in this test also performed well in the shrinkage and skid resistance tests.

Wattanasiriwech et al. (2009) investigated the use of waste mud in paving blocks. Waste mud is produced as a by-product in the production of ceramic tiles and is normally disposed of as waste in landfills. The production of ceramic tiles starts with the raw material being mixed and grinded, next it is granulated by spray drying, and then it is pressed, fired, polished and glazed. Waste mud is a deposit of washed down particles from this manufacturing process and is accounts for 2% of the final product weight.

Wattanasiriwech et al's research (2009) confirmed that it is possible to successfully prepare compressed paving blocks by using cement and waste mud together. Dry waste mud was collected from different areas on the disposal site. The waste mud collected had agglomerated, therefore, prior to mixing, the mud was hammer milled into a powder. Figure 2.2 shows the particle size analyzer used to analyse the particle size distribution of the milled mud. Next, the powdered mud was dried in a pre-set oven at 110°C for 24 hours; the average particle size was 370μm. Afterwards, Ordinary Portland cement (15–30 wt %) was thoroughly mixed in a mixer with the waste powder. Once a uniform colour was achieved, in order to allow compaction and hydrate the cement water (15-21% wt of cement-mud mix) was added (Wattanasiriwech et al., 2009).

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Figure 2.2: Particle size distribution of the waste mud after hammer milling into powder (Wattanasiriwech et al., 2009).

The study by Wattanasiriwech et al., (2009) found that blocks produced with 20% cement, after 14 days curing, produced sufficient strength results around 38 MPa, and 44 MPa after 28 days, the blocks exceeded the standard requirements.

On the other hand, Lam et al. (2007) indicated that with pulverized fuel ash (PFA) content, the 90-day compressive strength of concrete paving blocks increased with an increase in recycled crushed glass (RCG) content from 25% up to 75% RCG and the cement content was constant with 30% by weight. It was found that skid resistance and density reduced as the pulverized fuel ash (PFA) content increased. However, water absorption and abrasion resistance was not affected by pulverized fuel ash (PFA) content.

In Lam et al' research (2007), it was found that for paving blocks prepared with recycled aggregates, the water absorption of the blocks decreased as the recycled crushed glass content (RCG) increased. In this study, it was suggested that the use of

100% recycled material produces good quality and environmentally friendly paving blocks.

The recycled material in the paving blocks consist of 50% recycled crushed glass (RCG) and 50% recycled fine aggregate (RFA), an additional 10% of total aggregate weight of pulverized fuel ash was also added into the mix (Lam et al. 2007).
The sieve analysis of three types of fine aggregates used in this research is shown in Figure 2.3.

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Figure 2.3: Sieve analysis of three types of fine aggregates (Lam et al. 2007).

Turgut and Yahlizade (2009) investigated the use of fine and coarse waste glass in the production of paving blocks. In this study, the mechanical and physical properties of numerous levels of fine glass (FG) and coarse glass (CG) replacements with fine aggregate (FA) were investigated. The mix proportion in this research was 15% cement, 33% to 47% fine aggregates, 38% coarse aggregates and up to 14% by weight waste glasses. Experiments revealed that fine aggregates (FA) replacing fine glass (FG) at a 20% total weight replacement is viable in the production of paving blocks due to the pozzolanic nature of fine glass. When coarse glass (CG) was replaced by fine aggregate, there were only small beneficial effects in comparison to when fine aggregates replaced fine glass (Turgut and Yahlizade 2009).

The Gradation curves of the FA, CA, FG and CG are shown in Figure 2.4.

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Figure 2.4: Gradation curves of the FA, CA, FG and CG (Turgut and Yahlizade 2009).

In the various studies conducted by Chan and Poon (2006), it was witnessed that certain materials, such as high amounts of clay brick aggregate, timber, bamboo chips and lightweight materials used in the production of paving blocks had low results in compressive strength tests, most 30 MPa or less. Therefore, the strength of paving blocks produced with lightweight materials did not satisfy the minimum standard requirement.

2.3 The effect of reducing cement content in paving blocks

Cement content is a very important place in the production of paving blocks. Researchers have investigated ways to reduce cement content in different construction products in order to reduce the environmental impacts of the products and to benefit in terms of the economic costs (Naik 2008).

Recent researches have indicated that paving blocks could be successfully prepared by reducing the percent of cement content used. Research carried out by Ling et al. (2006) investigated the possibility of producing paving blocks with a 12% instead of 15% cement content, it was found that this was possible and it also satisfied the minimum compressive strength of 30 MPa as set out by MA20 standard for trafficked areas.

Wattanasiriwech. et al. (2009) conducted another research in which attempts were made to reduce the cement content of paving blocks by mixing waste mud with 15–30 wt % Ordinary Portland cement and water ratio 15–21 wt% was added. From all the blocks created, it was found that blocks consisting of developed strength rapidly and satisfied the minimum standard requirements after only 7 days of curing. The strength of the blocks consisting of 20% and 30% total weight cement, after 14 days, was 40 MPa and 54 MPa, respectively. These values exceed the standard requirement and are similar to the strength of cement mortar. It was also found that blocks containing 15% and 20% total weight cement took longer for strength development to occur as prolonged curing was required. The strength of blocks containing 15% cement satisfied standard requirements after 28 days whereas blocks containing 20% cement reached standard requirements at 14 days.

The study proved that compressed paving blocks can be prepared successfully by using a cement-waste mud mix.

Figure 2.5 below graphically plots the effect of cement content ratio on the development of compressive strength for the paving blocks.

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Figure 2.5: The compressive strength of different contents of cement over prolonged curing time (Wattanasiriwech. et al. 2009)

2.4 Relationship between density, admixtures, moisture content and compaction load in paving blocks

The density and strength of concrete paving block is affected in different ways depending on the cement content, water content ratio and compaction load. Obviously, if the cement content increases relatively to the optimum amount of water in the concrete mixture, it will result a better dry density and compressive strength (Ling et al., 2006). The main objectives of compressing blocks are to increase density, decrease void ratio, reduce porosity and water permeability, increase water resistance and hence enhance its durability (Bahar et al. 2004).

Wattanasiriwech et al. study (2009) investigated that the effect of compaction pressure on the strength of paving blocks containing 20% cement content cured for different periods with mix proportion as discussed in section 2.2 and 2.3. The results of his experiment are shown in Figure 2.6 below.

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Figure 2.6: Effect of compaction pressure on the compressive strength of paving blocks (Wattanasiriwech. et al. 2009).

At 25 MPa, the curing period required to meet 35 MPa was up to 28 days, while at 50 and 75 MPa, it required only 14 days. After 28 days curing, the strength of both blocks exceeded 40 MPa; which suggests that both compaction pressures might be more suitable than 25 MPa.

The precast concrete admixtures play a very important role in the compaction and density of paving blocks. Admixtures are mainly used in the manufacture of “semi-dry” vibrated and pressed concrete products. Dranfield (2012) states that the main use of admixtures are in paving and masonry blocks, bricks, flags and architectural masonry. Admixtures are used to assist in the compaction and dispersion of cement, colour and fine particles.

The strength of semi dry concrete can be increased by increasing the density and reducing the amount of un-hydrated or partly hydrated cement particles. Admixtures have an effect on the relationship between density and strength of semi-dry concrete as they have an impact on compaction and cement hydration.

Density is directly related to compressive strength and split tensile strength. A density increase of 50-70 kg/m^3 can cause compressive strength results to increase by 5-8N/mm^2 (12-18%), with similar improvements in tensile strength also (Dransfield 2012). The relationship between density and compressive strength is illustrated in Figure 2.7.

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Figure 2.7: The relationship between compressive strength and density (Dransfield 2012).

Admixtures increase compaction and density by causing a reduction in particle attraction that then causes an increase in the response to vibration and pressure.

Furthermore, admixtures affect the normal moisture content and density relationship by maintaining similar optimum moisture content (OMC) whilst achieving a higher mix density. Mixes that have lower water content hence lower optimum moisture content (OMC) will hinder compaction and may require longer periods of vibration, as a result, this will reduce output and the lack of compaction will reduce durability.

Whereas, mixes with a high water content, hence a higher OMC will have a lower density and may cause the units to stick in the mould making extrusion difficult, or may cause deformations to the units after extrusion.

The relationship between moisture content, strength and density according to Dransfield (2012) is illustrated below in Figure 2.8.

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Figure 2.8: The effect of moisture content on density (Dransfield 2012).

2.5 The effect of using waste materials and by-products to reduce cement content of paving blocks

Since 1970 researchers have been engaged in attempts to partially replace Portland cement with other suitable materials. Some pozzolans, limestone and metakaolin are possible materials which occur naturally; others such as Pulverised Fuel Ash and steel slag are produced by various metallurgy processes, with silica and other materials being by-products of various industries (Menéndez et al., 2002).

Fischer and Werge (2009) claim that about 850 million tonnes of construction and demolition waste is generated in the EU per year. This represents 31% of the total waste generated in the EU. Furthermore, the survey by McGrath group (2013) confirmed that nearly 40 million tonnes of recycled aggregates are produced in the UK each year which account for only about 20% of the total aggregates market (McGrath, 2013). Therefore this necessitates further recycling of demolition waste for use in construction products.

In research carried out by Ganjian et al. (2007) it has been reported that there are problems from the disposal of waste gypsum to landfill “it is estimated that over 300,000 tonnes per year of waste plasterboard for instance is produced on construction sites. It can also arise from strip-out activities during refurbishment and demolition projects, the waste arising from this source are significantly higher”.

Dunster (2008) showed that the addition of gypsum at quantities greater than 5% SO_3 (by weight of cement) to such cements (which contain calcium aluminate and calcium silicate hydrates) leads to a high risk of durability problems. This is because the excess sulphate reacts with the silicates and aluminates in the cement to form large amounts of expansive products, such as ettringite.

Ganjian and Pouya (2009) conducted research on the viability of blending plasterboard gypsum waste with a range of industrial wastes to produce a binder in the process of manufacturing paving blocks. Their aim was to find a feasible use for gypsum; which is one of the main waste products manufactured in the construction and demolition industry in the UK. Plasterboard gypsum (PG), basic oxygen slag (BOS), cement by-pass dust (BPD), run of station ash (ROSA) and Portland cement were utilized in this research.

They found that pastes consisting of plasterboard gypsum (PG), cement-by-pass dust (BPD) and basic oxygen slag (BOS) with the same water content of 15% produced good strength development. At 7 days, it was found that a mix of 10% plasterboard gypsum waste, 36% by pass dust and 54% of basic oxygen slag had the highest strength of 21 MPa and after 28 days the strength increased to 37 MPa.

Ganjian and Pouya's study (2009) proved that by using crushed plasterboard blended with BOS and ROSA as a cementitious binder, it is possible to produce binder paving blocks with desirable compressive strength and split tensile strength. However, a crucial factor to the strength of the binder paving blocks is the effect of water content on compaction and strength. Their results found that a water content of 15% is sufficient enough to achieve the desired strength and level of compaction in binder paving blocks, it is note that they did not make concrete paving blocks and did not test the durability of binder paving block.

Finally, this study found that when ROSA content was increase to more than 50% in the mixture of ROSA and OPC, the blocks had low compressive strength. A mix of 50% ROSA and 50% OPC achieved the highest split tensile strength of the experiment; with split tensile strength of 6.2 MPa at 28 days. At day 14, this mix had strength of 4 MPa; this passes the minimum requirement of the strength of paving blocks; which is 3.6 MPa. It was also found that run of station ash (ROSA) had acceptable pozzolanic potential to be used with slag, plasterboard and by-pass dust. As with Portland cement, the lower water content resulted in high strength.

2.6 History of the manufacturing of paving blocks in the UK

According to Lilley (1991) “concrete paving blocks were first manufactured in Germany at the end of the 18th century, also the first concrete block road was constructed at Neuss in Germany in 1936, using 240 x120 x 80 mm blocks and it was still in good condition some decades later”. Nevertheless, later on those manufactories were developed for the manufacture of paving blocks with economic issues in mind.

Lilley (1991) also states that “in the early 1970s few firms in the UK were equipped to manufacture paving blocks and their sales were insignificant, as they lacked the background knowledge to take their products much beyond use by private householders and into the public highway sector”.

It has been reported by Lilley (1991) that “the use of blocks for road construction was not considered seriously in the UK until the mid-1970s, when the decision to promote their application for this use was made, relying to a large degree on lessons learned from technical visits by engineers to Belgium, Holland, West Germany and Denmark ”. Following these visits, lectures, research and publication of various consultations and specifications were rolled out across the country for architects and engineers in central and local government as well as for current and potential manufacturers in the mid-1970s.

Commercially prepared paving blocks are subjected to a number of tests, such as split tensile strength, compressive strength, water absorption, freeze-thaw resistance, slip/skid resistance and abrasion resistance, these tests being based on significant research work conducted earlier on in situ concrete.

Furthermore, the construction of paving blocks as they now exist was helped considerably by these earlier architects and engineers who had the responsibility for planning and construction and who made extensive use of paving blocks for a range of different types of roads and purposes, going far beyond their use in purely residential roads and reaching into the commercial and industrial areas of cities.

This experience has given other possible users confidence in the idea as well as providing current and future manufacturers with an incentive to invest in up to date production facilities on a large scale. According to Lilley (1991) "the firm of Fielding and Platt manufacturers of large hydraulic presses, invented a method of pressing concrete which has since become known as the wet-press process". This mechanism allows for high-speed production with good quality and extremely uniform production and therefore it was much cheaper than stone flags. As a result, by the mid-twentieth century most urban footways in the United Kingdom were made up of paving blocks. In addition, there are many blocks of differing shapes currently in the UK market although all of these shapes were developed abroad. (Lilley. 1991).

2.7 Colours, finishes, shapes and sizes of paving blocks

The constantly increasing range of shapes, colours, sizes and finishes which are used in the manufacture of paving blocks means that they can be laid in a variety of bonding and laying patterns so that they can be used to create an architectural effect for instance, or to highlight a specific feature. There are blocks where more than one colour is used and blended together in the manufacturing process, resulting in multi-coloured. The great advantages of concrete paving blocks as an alternative is that they are cheaper to manufacture and provide a superior slip resistance which makes them an easier and therefore more accessible surface for pedestrians to use.

The work size thickness of paving blocks between 60mm and 100mm. (Interpave. 2012).

2.8 The component layers of a typical concrete paving block pavement

Figure 2.9 presents the fundamental elements of the construction of a typical concrete paving block pavement.

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Figure 2.9: The cross-section below layer of pavement including paving blocks (Interpave. 2012).

2.9 Preparation of restraints edge restraints

In order to prevent movement, either the whole paved area or the individual blocks must be restrained at the edges. This ensures resistance to lateral movement and prevents the paving blocks from rotating when a certain load is applied; it also restricts loss of coarse material, as they no longer have to be added at the boundaries. The restraint edges should be suitable for its application and, if likely to be overrun by vehicles, it should be sufficiently robust to resist displacement. Figures 2.10 and 2.11 illustrate different edge restraints used for various situations.

Figure 2.10: Light vehicle and pedestrian traffic (Interpave. 2012).

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Figure 2.11: Estate roadways/car parking areas (Interpave. 2012).

2.10 Construction of the paving block layer

In terms of placing the paving block layer in the correct position, paving blocks can be hand or machine laid and usually starts at a fixed edge restraint. If the edge restraint is not straight or is at 90° to the intended paving block, then a temporary string line datum should be set up at a short distance from the edge restraint; this will help align the first row of paving blocks. A second string line at 90° to the first string line should then be applied to ensure the paving blocks do not wander and move.

Paving blocks can be cut and used to fill in the area between the first string line and edge restraint. During the laying of the paved area, it is recommended to continue using the string line method or use other appropriate control methods. When laying paving blocks, joint widths of 2-5mm should be left in the specified bond. Some paving blocks have spacer nibs that are not designed to fix the joint;, instead they prevent damage occurring to the paving blocks after face-to-face contact. When hand laying paving blocks, the person installing the paving blocks should use paving blocks already laid as a guidance and take care not to disturb them. Full paving blocks should be laid first by using an open laying face. Figure 2.12 represents how this is done.

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Figure 2.12: Using an open laying face (Interpave. 2012).

2.11 Block laying patterns

The fact that concrete paving block is made in such a range of shapes, sizes and colours, means that designers have the scope to use them to create a number of different patterns and designs. When the paving is being used for pedestrian areas, serviceability of the paving is the priority and the pattern in which the blocks are laid is of secondary importance. Where the service is to be used by vehicles, the most effective pattern is a herringbone design.

Where herringbone is used the performance of the pavement is not impacted by the direction of the herringbone bond in relation to the direction of the vehicular areas. A herringbone pattern is usually set at an angle of 45º or 90º to the straight edge of greatest length. Although it is possible to use rectangular units to form stretcher bonds, it is important that such a stretcher bond is not set down in the same 'line' as that of the general traffic flow.

2.11.1 Stretcher bond

Stretcher bond is most appropriate for use in pedestrian areas and for those areas where use by traffic is very light and where turning movements, braking and acceleration are infrequent. Where it is used it should be laid at right angles to the usual flow of the traffic.

Figure 2.13 shows stretcher bond.

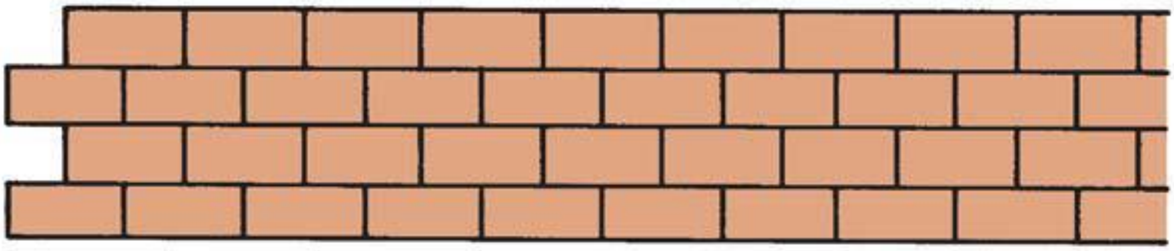


Figure 2.13: Shows stretcher bond.

2.11.2 Basket weave or Parquet

This pattern should only be used in pedestrian areas and not in areas where there is traffic, as shown in figure 2.14 below.

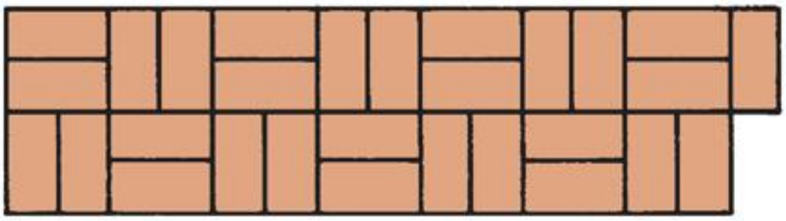


Figure 2.14: Shows basket weave or parquet.

2.11.3 Herringbone at 90º and 45º to an edge

A herringbone pattern can be used in any situation, and where it is used, whether it is laid at 90º or 45º it should be oriented so that the longest straight edge is parallel with areas used by vehicles since this arrangement will bring about a reduction in creep and allow the wheel loads to be more evenly distributed through the pavement below them (Interpave. 2012).

Figure 2.15 and 2.16 shows herringbone at 90º and 45º to an edge.

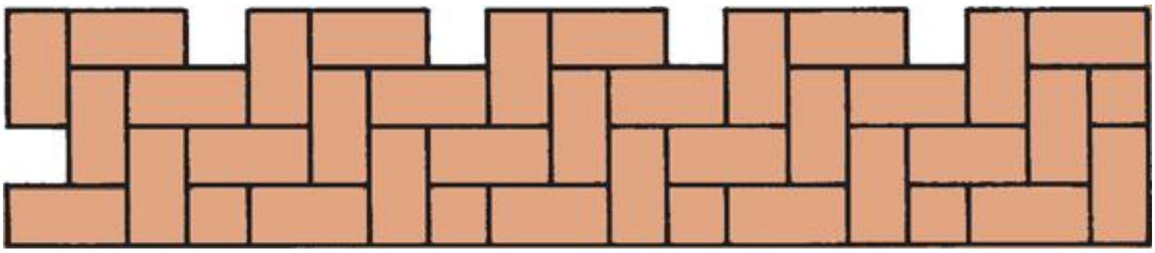


Figure 2.15: Shows herringbone at 90º to an edge.

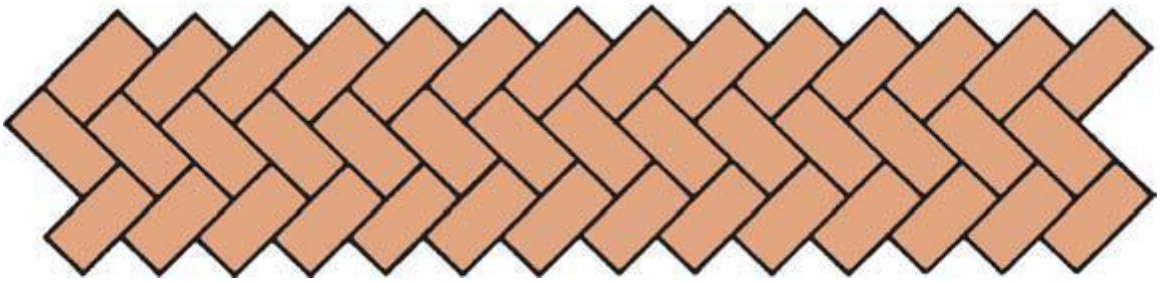


Figure 2.16: Shows herringbone at 45º to an edge.

2.12 Paving blocks manufacturing

The paving block should be made in a factory with following minimum facilities:

2.12.1 Concrete paving blocks machines

The machine used in the manufacture of paving blocks should have the capacity to produce paving blocks of a high quality by providing a high level of compaction through the use of hydraulic compaction pressure and high intensity vibration to the moulds. In order to give uniformity of strength the machine must have an automatic control panel.

2.12.2 Concrete batching & mixing plant

It is important to keep to the design for the concrete mix for the manufacture of every batch of material and the manufacturing plant should have available an automatic control panel so that there is no variation in the water cement ratio from batch to batch in order to provide concrete that has consistent strength and quality. The plant must have a mechanism to enable the loading of the raw material into the mixer and onto a conveyer belt so that it can be efficiently transported to the machine which will make it into concrete blocks.

2.12.3 Curing

There should be a well designed curing area within the factory so that the paving blocks can be adequately cured. The curing is usually done at 20±2°C and 98% RH.

2.12.4 Aggregates

Those natural aggregates to be used to make the concrete paving blocks must meet the appropriate aggregate requirements, the maximum size of the aggregate that can be used being 6.0 mm. Where circumstances dictate it is possible to use a small size of 4.0 mm or the smaller size may be chosen in order to create a specific surface texture. In general, where it is possible to use coarse particles, this can result in savings in the binder so long as the mix is appropriately proportioned.

2.12.5 Water content

The water used in the process should be clean and should not contain any harmful substances, although the optimum moisture content (OMC) is dependent upon the materials that are used, the quality of vibration and the moulding equipment used. Adequate compaction will not be easy to achieve if the moisture content is below (OMC) and it may also be necessary to subject the mix to a longer period of vibration and this will negatively affect output. Any lack of compaction will reduce the life of the product. If too much water is used the density of the mix will be reduced which may result in units becoming stuck to their moulds so that extrusion becomes difficult; it may also cause units that can be extruded to subsequently become deformed.

2.13 Uses of paving blocks

Over recent decades paving blocks has been used in a number of situations; it has provided flooring, coverings in passageways and on drives; it has been used for some roads in towns, in gardens and for car parking areas; it is able to meet a great many of the needs of architects and of road engineers and, in particular, those of the general public.

Portland cement is the main material used to produce paving block and "concrete block pavement has many benefits including ease of maintenance and repair, easy access to underground utilities, low maintenance costs and the availability of different shapes and colours that are both functional and attractive" (Chan and Poon. 2006).

One of a number of benefits that the use of paving block brings is that its technical specification means that it has good resistance to softening and to penetration by oil spills; it also has a hard surface that is able to resist indentation from high stress that occurs locally, for instance from the weight of storage racks, although it is not entirely resistant to stains. It is also impossible to avoid settlement at some points without making the product unacceptably expensive. However, should the settlement that occurs be too great to allow the roadway to function efficiently, it is possible to remove segments of paving units in order to allow for the readjustment of the bases, after which the units can be re-laid.

Nowadays, researchers know that recycled materials play a very important part in the production of paving blocks for a number of reasons. First of all, it is able to achieve better characteristics in the paving blocks; secondly, it helps to minimize the price of materials as well as using different waste materials to ensure the ability of constructions to meet the aims. The main examples of using paving blocks are:

- **Bulk storage areas**

Another use for paving blocks has been in areas used for the storage of bulk materials for instance coal and aggregates, where it is able to prevent the inter-mixing of the materials being stored with the ground beneath them, as well as providing a working surface for mechanical shovels and vehicles used for delivery. (Lilley. 1991).

- **Bus terminals and stops**

In urban areas paving problems have arisen from the use of the buses that provide public transport since these vehicles carry high wheel loads and at those points where there are either bus stops or terminals their wheel tracks and the associated loads will be concentrated to a greater extent than on the public roads. A further problem is created by the considerable spillage that often occurs with surfaces that use bituminous materials not performing well once they have been softened by oil making them no longer able to support heavy loads. This has made paving blocks the surface of choice for many bus lanes, stops and terminals. (Lilley. 1991).

- **Car parks**

Paving blocks offer considerable advantages when used to surface car parks at ground level, being cheaper to use than in situ concrete or bituminous material as well as having a more pleasing appearance so that the walk from a parking spot is more attractive. (Lilley. 1991).

- **Cycle tracks**

These have an important use in a number of countries where they allow for the separation of pedal cyclists both from faster moving cars and from slower moving pedestrians. Whether or not cycle tracks are developed is dependent in the first place on topography since they are far more likely to be built on flat land where it is easier to cycle. Where they are built paving blocks are often the chosen surface in a number of countries. (Lilley. 1991).

- **Emergency roads**

It is necessary in some situations to ensure that there are paved areas in places where heavy vehicles would not normally be expected to have access that are suitable for use by emergency vehicles. However, to arrive at an economic design for such an area is not easy using either in situ concrete or a bituminous material, and where a pavement has been designed in anticipation of light traffic only but then has a heavy load using it the result can be that the pavement fails or even that it is completely destroyed. An important advantage that accrues from the use of flexible paving blocks is that there is the possibility of resurfacing the affected part of the pavement in the event of overloading resulting in excessive deformation. (Lilley. 1991).

- **Farm roads and yards**

The use of agricultural vehicles and implements imposes a severe stress on any paving and there are relatively few practical solutions available. The most recently used surface for such farms and stable yards has been precast concrete block paving which gives those organising the farm the option of constructing the yard or access at a time that is most convenient in relation to the working of the farm.

In order to save on costs farm roads are narrow, most usually about 3 metres wide. (Lilley. 1991).

- **Footways**

In earlier periods it was difficult to provide clean walkways for the use of pedestrians in built up areas. However, once manufacturing techniques were available that enabled cheap paving blocks of accurate dimensions to be made, their widespread use to provide the surfaces for walkways in urban and residential areas was quickly established. (Lilley. 1991).

- **Garden centres**

Wide use is made of prefabricated paving in garden centres and it is also sold at these outlets along with plants, tools for gardening and other gardening requisites. When it is used within the display areas of such outlets, the simple and clean paving that it gives enables customers to have a pleasant experience as they move around to look at plants and in greenhouses. Such paving has the added advantage of being portable which means that it is possible to re-use it as and when changes to the display layouts demand. (Lilley. 1991).

- **Hard shoulders**

Problems can arise in relation to the paving of the emergency lanes that are necessary to the side of high-speed roads, or else where it is necessary to have cross-over lanes between carriageways for use by emergency vehicles, and these problems become more acute where such surfaces have to be constructed once the original road is being used by traffic. In these circumstances paving blocks that have been designed specifically to carry the heaviest kinds of traffic are able to provide a solution. (Lilley. 1991).

- **Industrial estates**

Where paving blocks are used for surfaces on industrial estates they have the advantage of being able to cope with a range of loads while at the same time having an attractive appearance and providing flexibility, allowing them to be used to pave complex shapes and where there are variations in the levels of the surfaces. When all these attributes are considered, it can be seen that paving blocks are able to provide the ideal surface for many uses in an industrial setting. (Lilley. 1991).

- **Junctions**

Paving blocks are used in order to bring about safety improvements at road junctions on urban and residential roads. After tests had been carried out to determine the extent of surface rutting, stopping distances, noise levels and the reactions of drivers, it was found that block paving was advantageous in every area and therefore could make a substantial contribution to improving road safety in built up areas. (Lilley. 1991).

- **Landscape paving**

The fact that the different unit sizes of the paving block are small means that the designer has greater scope to sculpt the paving since it is easier with small sizes to follow the line of a curve in both a horizontal and vertical plane. (Lilley. 1991).

- **Mini-roundabouts**

Mini roundabouts, which can be built in a much smaller space than a full roundabout, are built with the purpose of giving guidance and by this means enabling a better flow of traffic at road junctions where the designated traffic speed is between 50 and 60 kilometres an hour. They are smaller than a full roundabout with a typical diameter of 2 metres and they are built flat or, more often, in a shallow domed shape. The dome exists to discourage drivers from driving straight across the roundabout while at the same giving space for longer vehicles to negotiate the roundabout relatively easily by allowing their real wheels or any attached trailer to travel over the dome. Paving blocks perform well as surfacing for these domes. (Lilley. 1991).

- **Pedestrian crossings**

Certain parts of carriageways are designated for use by pedestrians as uncontrolled crossing points and they are most frequently delineated by marking the relevant part of the carriageway with a line of alternating black and white stripes which has given them the name of zebra crossings. The use of black and white tops makes these stripes easy to create and also hard wearing. (Lilley. 1991).

- **Petrol stations**

For a number of reasons in Europe retail outlets that sell petroleum most frequently have a surface made up of paving blocks. One reason for this is that oil-based surfacing materials are easily damaged by any substantial spillage and although in situ concrete will resist damage, unless it has been carefully constructed it can be unattractive, whereas multi-coloured paving is intrinsically attractive and can form a patterned pavement and can also be laid in such a way that there is easy access to underground pipes, electrical cables and storage tanks, allowing for servicing. (Lilley. 1991).

- **Playgrounds**

The surface of children's playgrounds is sometimes composed of paving block particularly if the playground is used for car parking out of school hours. This method of paving enables patterns to be built into the surface by the use of blocks of varying colours, providing for instance large scale chess boards and allowing for it to be used as an all all-weather games area. However, falls on a hard surface can result in injuries and this constitutes a disadvantage for this type of paving. (Lilley. 1991).

- **Railway station platforms**

At the time that railway systems were developing rapidly across the globe the need for ease in boarding the train led to the construction of raised platforms on which paving blocks have been used to provide the surface. (Lilley. 1991).

- **Roundabout**

The purpose of roundabouts, which have been widely used for many years, is to control the flow and speed of traffic at road junctions. Frequently the central part of these roundabouts is planted up in some way with flowers or other vegetation, but not with large trees which could obscure the view of the complete roundabout so that drivers mistake their shape and purpose and go the wrong way on them. In order to minimise the risk of any accidents at roundabouts, many of them have been given skirts with a pattern of white-topped and black-topped blocks in order to make them more visible. (Lilley. 1991).

3. Materials used in this research:

3.1 Plasterboard gypsum

For this research crushed Plasterboard Gypsum (PG) waste was supplied by Lafarge plasterboard recycling plant in Bristol. Plasterboard waste can arise on construction sites for a number of reasons, including wasteful design, off-cuts generated during installation, damaged boards, and over-ordering (Dunster, 2008)

Once plasterboard gypsum waste had been sourced from a number of sources, such as construction and demolition sites, it was recycled and then carefully classified, ensuring that during the process all contaminants such as paper and glass had been eliminated.

The big pieces of paper and other contaminations were separated by using a series of sieves before the gypsum was crushed using a metal tamper. Plasterboard was then ground, sieved and conditioned to form a powder. The analysis of the particle size of the gypsum was made using a Malvern Mastersize 2000 laser analyser with an accuracy of ± 1%. As a result, the particle size was found to be between 1 µm and 1 mm in diameter, and mostly >300 µm (Ganjian and Pouya, 2009) as shown in the figure 3.1.

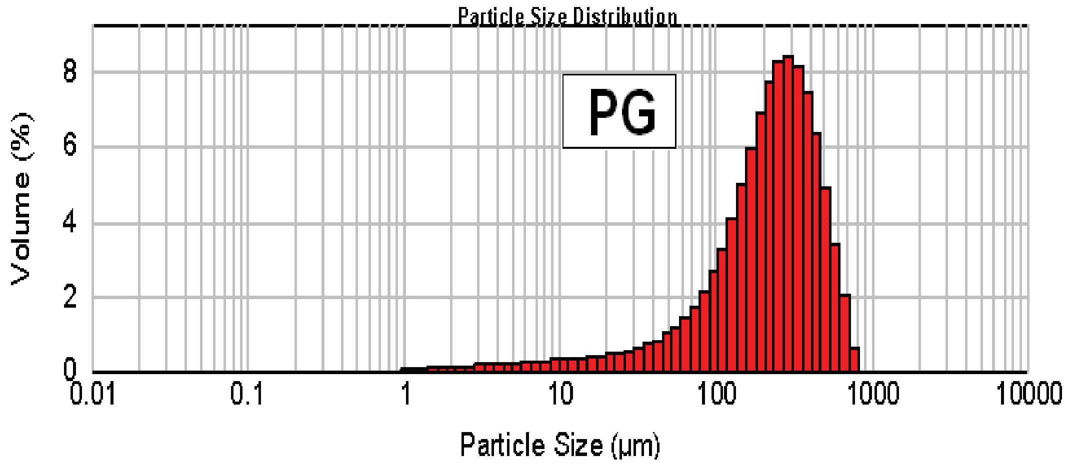


Figure 3.1: Particle size analysis of crushed and sieved PG

3.2 Basic oxygen slag

The basic oxygen slag for this research was obtained from the Corus plant at Scunthorpe. Basic Oxygen Slag (BOS) or steel slag dust is a by-product that results when iron is converted to steel using a basic oxygen furnace or from melting scrap to make steel in an electric arc furnace (Caiju, 2004). During the current production of steel it is inevitable that basic oxygen steel slag will be produced, for each tonne of steel produced, an estimated 300 kg basic oxygen steel slag is consequently produced (Moreno, 1999). In the UK approximately one million tonnes of basic oxygen slag is produced each year with about ten million tonnes of it being stored for weathering so that free lime can hydrate (Ghataora et al., 2004). Furthermore, in 2006 the United States had an iron and steel slag output of approximately 21.5 million tonnes, with 40% being classified as steel slag. In the previous three years, the output of steel was estimated to have been 8.8 million metric tonnes, 40% of that being classified as steel slag (Van Oss, 2003). Where possible the use of basic oxygen steel slag is favoured in US production, not only because this prevents unpleasant slag accumulates being produced but also because it means there is less needs for finite primary materials to be used.

Figure 3.2 shows that the average particle size is between 40-60 µm.

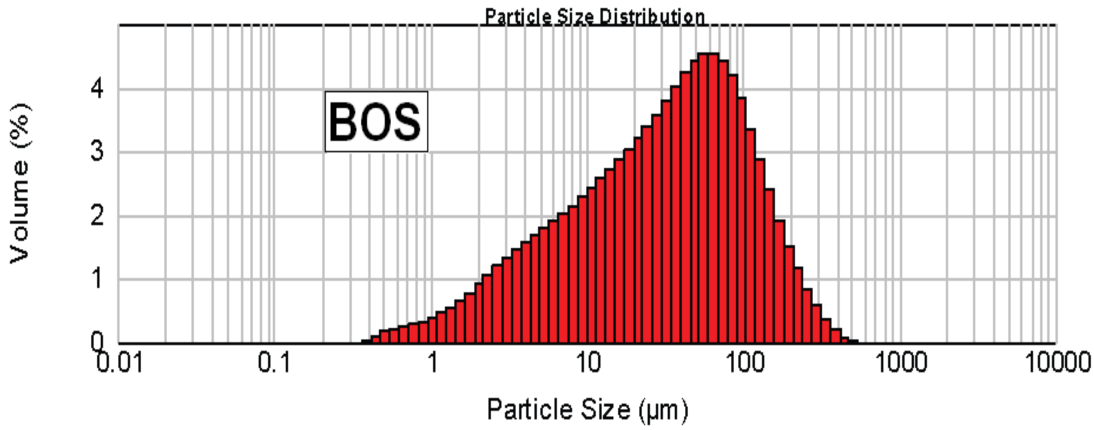


Figure 3.2: Particle size analysis of ground BOS

3.3 Run-of-station ash

For this research dry Run-Off-Station Ash (ROSA) has been obtained from Rugby Ash. In this case, the run-off-station ash is derived from a power station with an average particle size of 20 micron. Run-off-station ash is an unclassified Pulverised Fuel Ash collected from the chimney stacks of power stations. It is pozzolanic and reacts with calcium hydroxide and alkalis to form cementitious compounds, such as calcium silicate/aluminate hydrates. Run-of-station ash (ROSA) has been used in concrete and paste mixes, and prepared as a fine powder.

Figure 3.3 shows the particle size analysis for run-of-station ash.

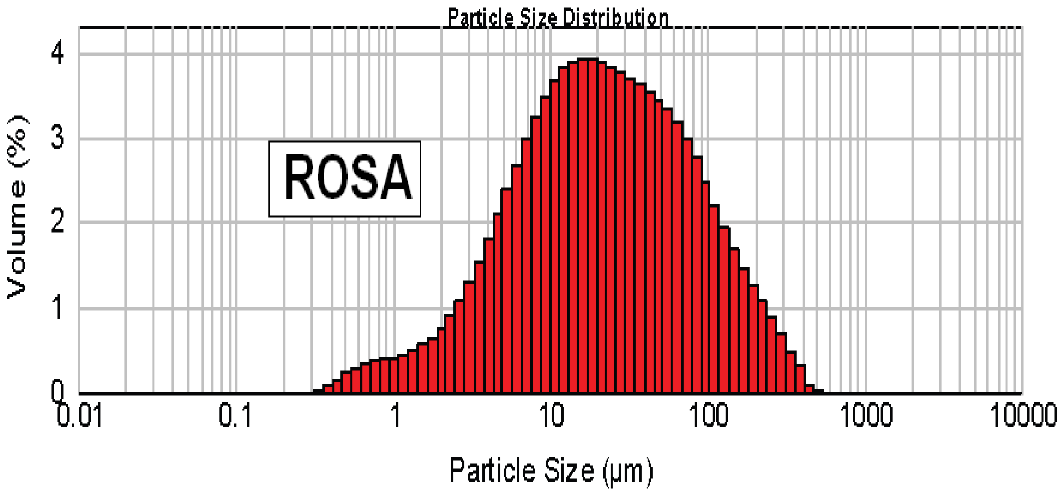


Figure 3.3: Particle size analysis of ROSA

3.4 Cement by-pass dust

By-Pass Dust (BPD) is collected from the kiln bypass. The main purpose of the kiln bypass is to bleed off volatile materials that would otherwise re-circulate around the kiln and pre-heater system. When by-pass dust is condensed in cooler parts of the kiln it may lead to blocking the kiln or eventually may end up in the cement clinker. The temperature is of utmost importance for the BPD; BPD can only be removed from the kiln at 1000°C. As a result, BPD contains numerous cement bound phases.

BPD from a local cement works, Castle Cement (Heidelberg cement group in Rugby, UK) was obtained for this research. The BPD was provided in powder form, the average particle size was 10µm, and the maximum particle size was noted to be 200 microns.

Figure 3.4 shows the results of particle size analysis.

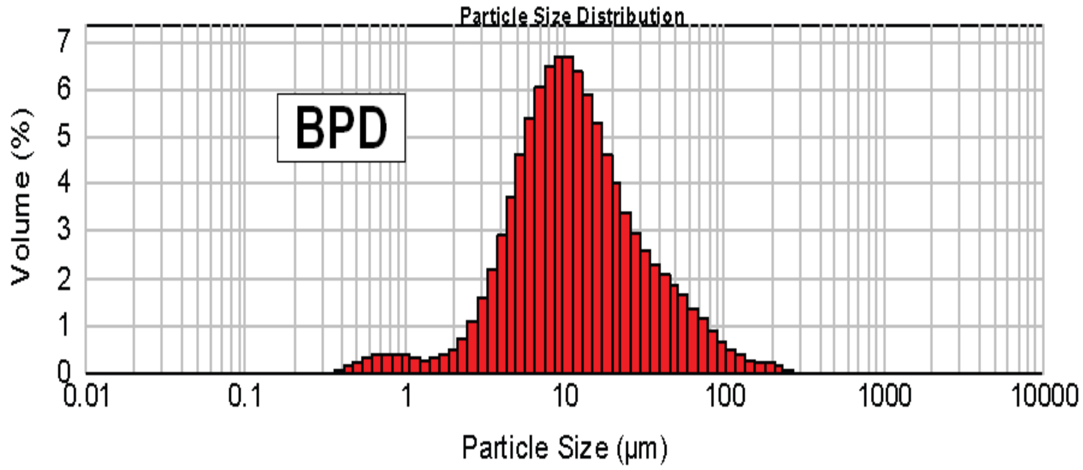


Figure 3.4: Particle size analysis of BPD

3.5 Ground granulated blast furnance slag

Ground Granulated Blast-furnace Slag (GGBS) is a cement substitute, manufactured from a by-product of the iron-making industry. If ground granulated blast-furnace slag is combined with Portland cement, satisfactory cementitious materials such as Portland-slag cement and blast furnace cement can be produced.

Within the UK ground granulated blast-furnace slag is produced and generally sold as a powder which can then be batched and mixed in a blender to be put to use in the construction industry for the provision of concretes, grouts and mortars. According to the Cementitious Slag Makers Association each year in the UK two million tonnes of ground granulated blast-furnace slag in the cement industry are used.

Using ground granulated blast-furnace slag with concrete has many advantages, including improved durability, workability and economic benefits (American Concrete Institute, 2003). Ground granulated blast-furnace slag essentially consists of silicates and alumina silicates of calcium and other bases that are developed in a molten condition simultaneously with iron in a blast-furnace. The chemical composition of oxides in ground granulated blast-furnace slag is similar to that of Portland cement but the proportion varies (Dubey, 2012). The ground granulated blast-furnace slag (GGBS) was obtained from Civil and Marine, a part of Hanson UK, and the grain sizes in the range between 0.3μm and 0.1mm, with an average particle size around 20μm. The material was marketed under the BS EN 15167-1-2 standard (British Standard Institute, 2006).

Figure 3.5 shows the results of particle size analysis.

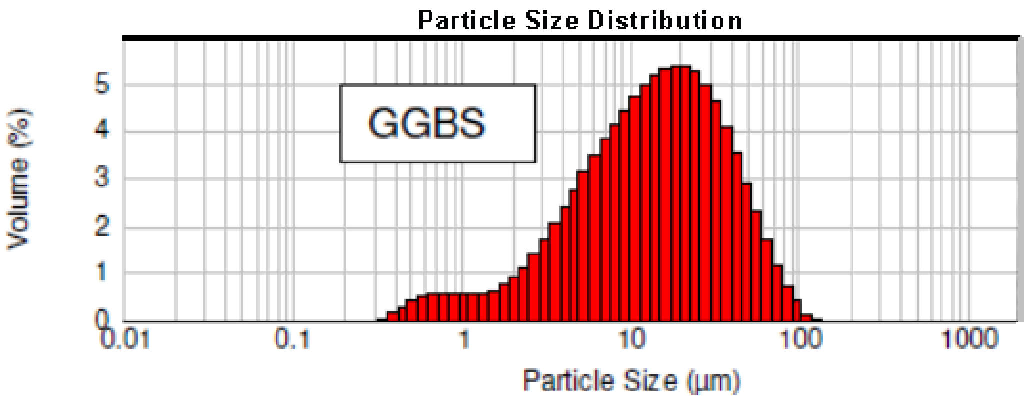


Figure 3.5: Particle size analysis of GGBS

3.6 Ordinary Portland cement

The cement is the primary operative constituent of concrete and it is normally an expensive component and therefore its effective use is important if the greatest degree of economy and stability is to be the result for any specific concrete mix.

Types of Portland cement which are able to provide the necessary degrees of strength and stability are those most favoured by the producers of concrete. However, other types of cement which also have the necessary key characteristics to a high degree can also be used for some purposes. For this research the cement used was CEM1 cement as defined by BS EN 197-1 (British Standard Institute, 2011).

Figure 3.6 shows the results of particle size analysis.

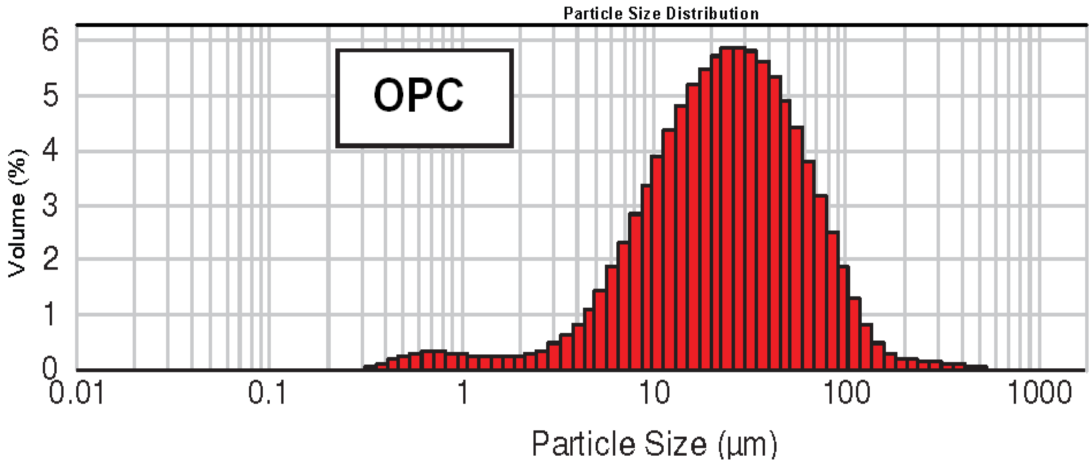


Figure 3.6: Particle size analysis of OPC

3.7 Aggregate

Sieve analysis is commonly known as "Gradation Testing", and it is essential for all engineering work. Two different maximum sizes, 4mm and 6mm, natural crushed quartz aggregates were used in this study.

Furthermore, in this research 4mm and 6mm aggregates from different sources were used to replacement the natural aggregates and the properties of aggregates derived from different sources as shown in Table 3.1.

Table 3.1: Properties of aggregates derived from different sources

Type of Aggregate used	Density-SSD (kg/m^3)	Density-Oven dry (kg/m^3)	Water absorption (%)
Sand	2021	1986	1.76
4mm Natural aggregate	2718	2660	2.18
6mm Natural aggregate	2691	2661	1.15
4mm IBAA	2253	2002	12.52
6mm IBAA	2119	2006	5.66
6mm RCA I	2289	2166	5.67
6mm RCA II	2183	2053	6.34
4mm RCG	2342	2224	5.29
6mm RB	2163	2017	7.26

The sieve analysis of 4mm and 6mm aggregates used for concrete paving blocks is shown in Figures 3.7 and 3.8.

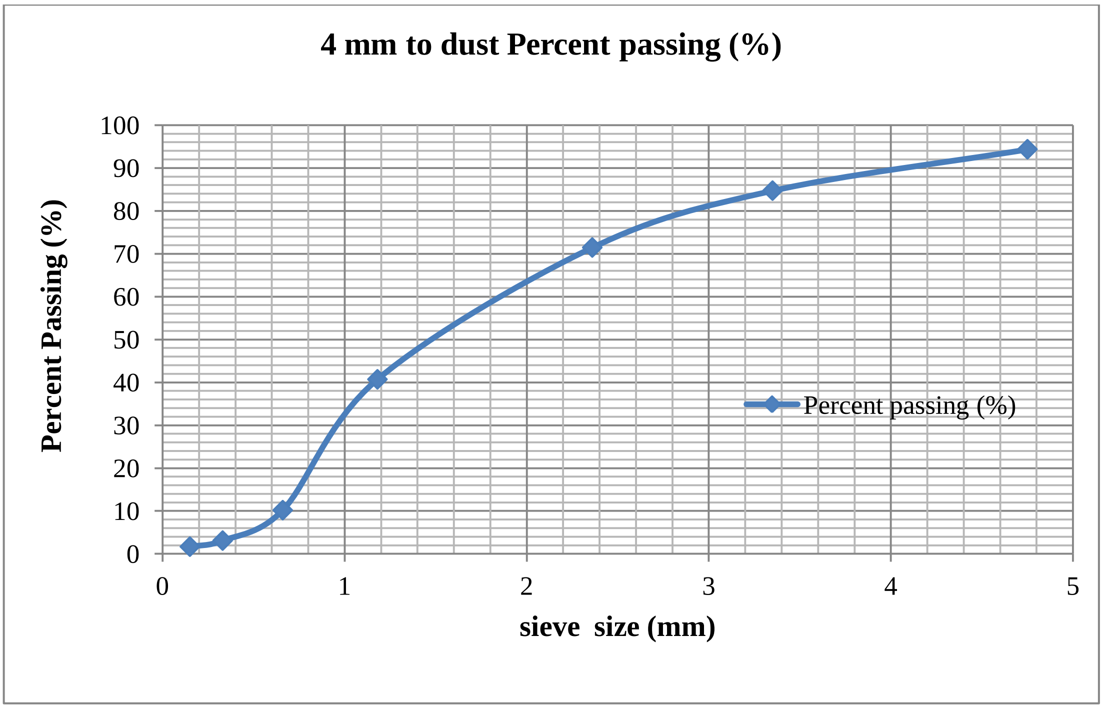


Figure 3.7: Sieve analysis of 4mm aggregates

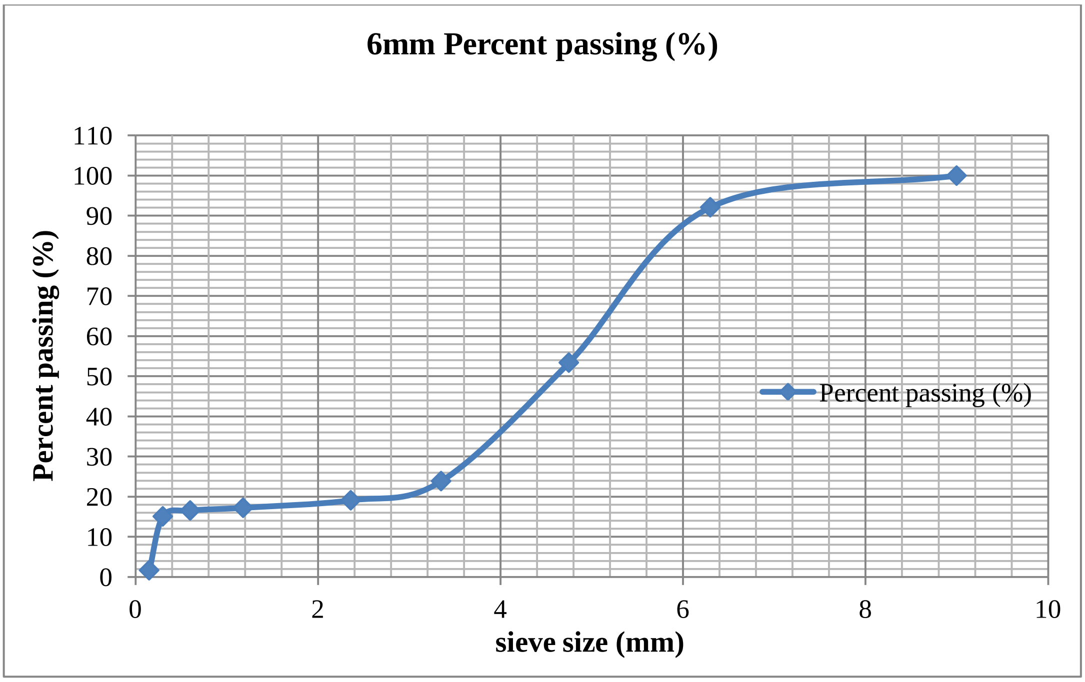


Figure 3.8: Sieve analysis of 6mm aggregates

3.8 Incinerator bottom ash aggregate

In this material the term ‘ash’ is slightly misleading because the material is not pure powder; it also contains traces of glass, brick, rubble, sand, grit, metal, stone, concrete, ceramics and fused clinker as well as combusted products, such as ash and slag. Incinerator Bottom Ash Aggregate (IBAA) is an environmentally friendly material with a consistency, which makes it easy to handle and use.

In this research incinerator bottom ash aggregate (IBAA) was obtained from Day Group LTD and the sizes used were 4mm and 6mm.

The sieve analysis of 4mm and 6mm IBAA used for concrete paving blocks is shown in Figures 3.9 and 3.10.

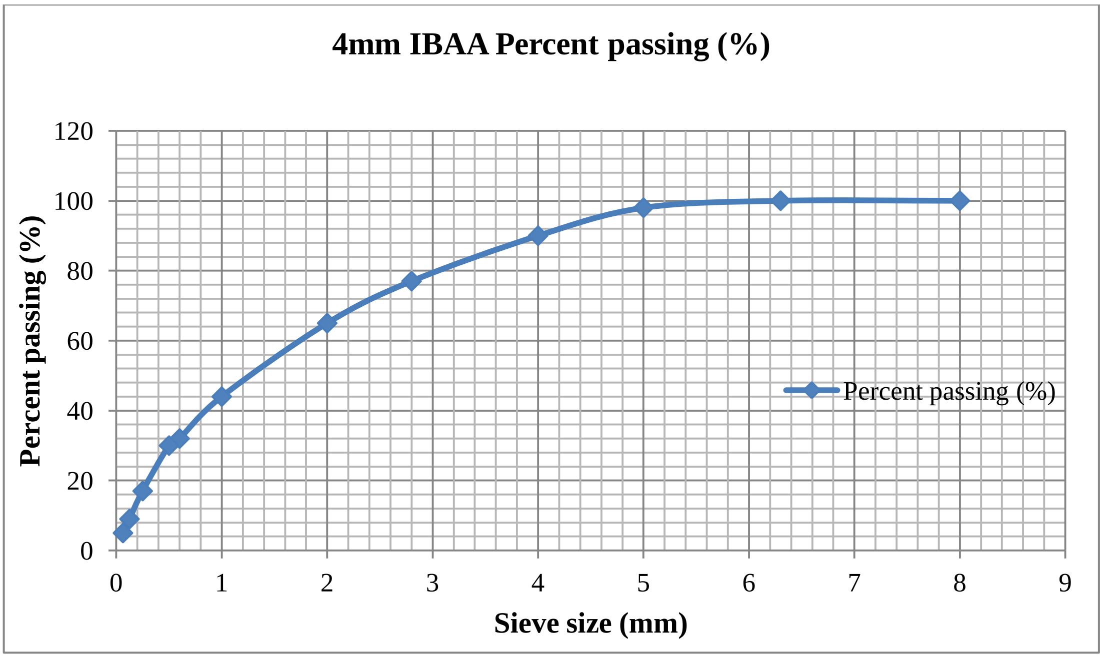


Figure 3.9: Sieve analysis of 4mm IBAA

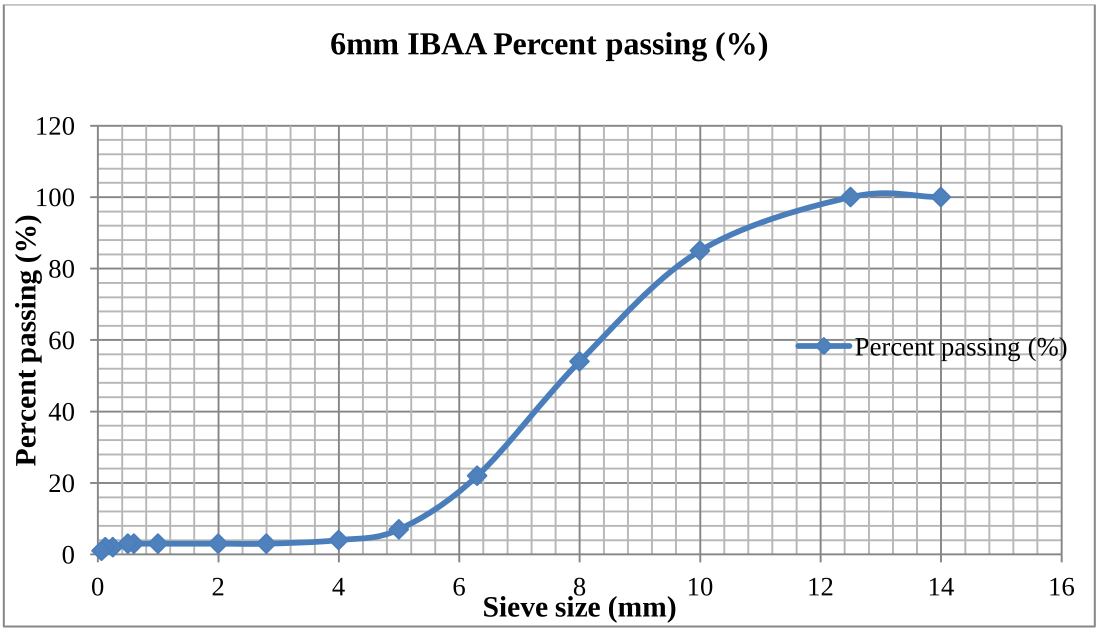


Figure 3.10: Sieve analysis of 6mm IBAA

3.9 Recycled crushed glass

When used in construction applications, waste glass must be crushed and screened to produce an appropriate design gradation (Turgut and Yahlizade, 2009). Crushed glass or cullet, if properly sized and processed, can exhibit characteristics similar to that of gravel or sand.

For this research recycle glass was obtained from Day Group LTD, 4mm natural aggregates were replaced with Recycled Crushed Glass (RCG) of the same grading. Some physical properties of RCG are given in Table 3.1.

The sieve analysis of 4mm RCG used for concrete paving blocks is shown in Figures 3.11.

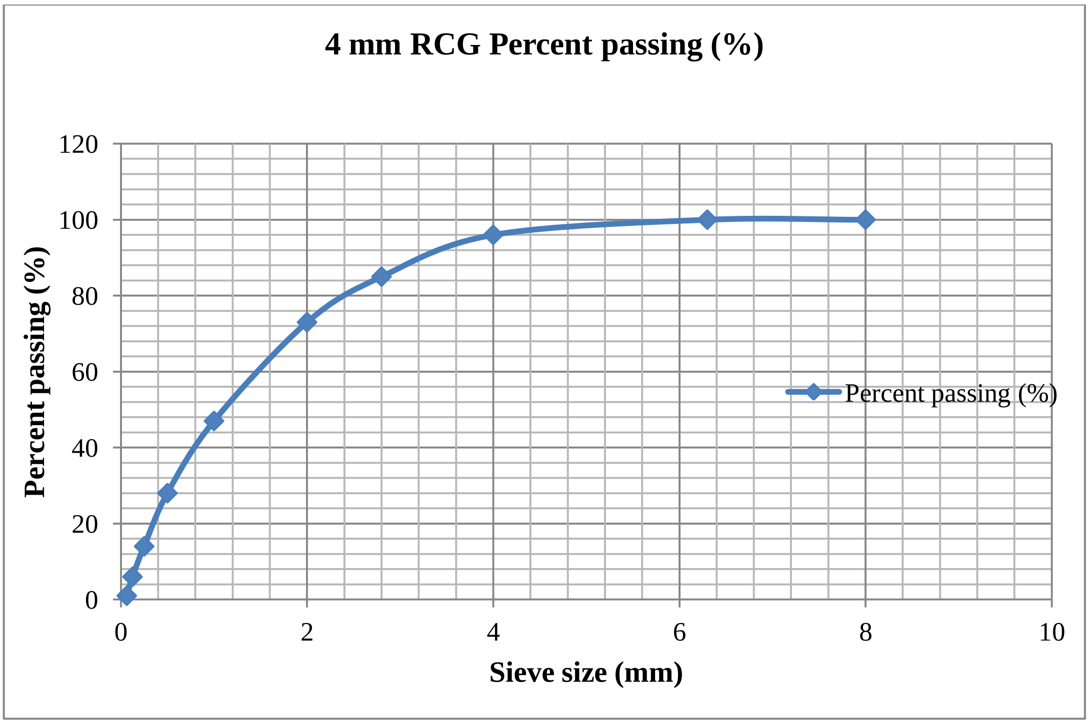


Figure 3.11: Sieve analysis of 4mm RCG

3.10 Recycled concrete aggregate

Recycled concrete aggregates are aggregates derived from the processing of materials previously used in construction. For this research Recycled Concrete Aggregate (RCA) was obtained from the civil engineering laboratory at Coventry University. Two types of RCA were used: RCA I, this consisted of normal concrete cubes and RCA II which consisted of normal concrete slabs. For the production of paving blocks the used concrete cubes and slabs were firstly crushed manually using a hammer, and then sieved to a required grade, finally, they were ready for use as a 100% replacement for 6mm natural aggregates.

The same grading as shown in Figure 3.8 for 6mm was used, and some physical properties of (RCA) are given in Table 3.1.

3.11 Recycled bricks

Clay brick is mainly produced in construction and demolition sites where it is most commonly delivered to landfills or reclamation sites for disposal. As landfill space and reclamation areas are becoming more and more limited, it is important to explore the possible use of crushed clay brick as a civil engineering material.

This study investigated the use of crushed brick to fully replace 6mm natural aggregates in paving blocks. The Recycled Brick (RB) for this study was delivered to the laboratory from a demolition site in Coventry University campus. Similar to the RCA, the bricks were crushed manually using a hammer, and then sieved.

The grading of the brick aggregate was similar to the 6mm grades used in the factory. The same grading as shown in Figure 3.8 was used, and some physical properties of (RB) are given in Table 3.1.

3.12 Steel fibre

Steel wire Fibre (SF) was obtained from Krampe Harex; the wire had hooked ends 35 mm in length and 0.55 mm in diameter with a tensile strength of about 1250 N/mm^2.

3.13 PVA-Fibre

PVA Fibre can be used in paving block production as it has high adhesive strength, so it is hard to pull out from the cement matrix, and it also has anti-cracking and reinforcement properties. Moreover, PVA-Fiber has high split tensile strength and excellent mechanical properties. The PVA-Fibre was obtained from BHL group; the length of fibre used in this research was 6mm.

3.14 Sand

In this research the sand used was obtained from the factory. And the sieve analysis of the sand used for concrete paving blocks is shown in Figure 3.12.

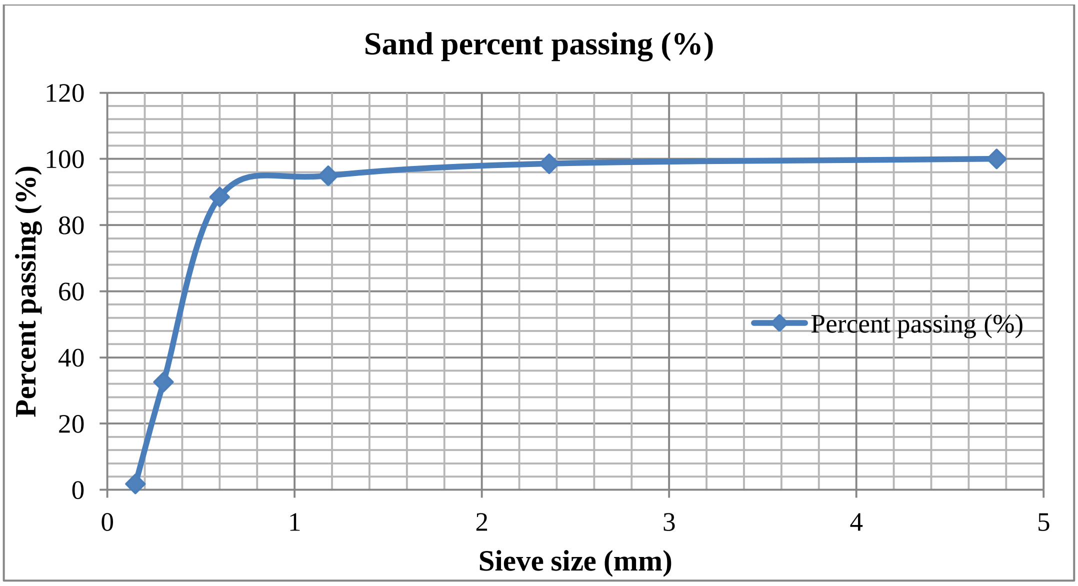


Figure 3.12: Sieve analysis of the sand used

3.15 Water

Tap drinking water of the city of Coventry was used to make the paste and concrete mixes.

4. Methodology and test methods

The main methodology in this research was based on the different standard tests required by British standard and industries. These tests include compressive strength, split tensile strength, slip/skid resistance and weathering resistance (freeze/thaw resistance and water absorption) to achieve the requirements required.

The experimental programme included three phase studies which are explained in section 5.2.

4.1 Compressive strength test

The compressive strength of the cubes samples can be defined as the measured maximum resistance of a concrete to axial loading. The uni-axial compression test is the most common test used to test the hardened concrete specimens because this test is easy to do. This test will be done after 14 and 28 days and each sample will then have its weight measured.

The compressive strength of the specimens was determined using a compression testing machine with a maximum capacity load of 2000kN, according to BS EN 12390-3 (British Standard Institute, 2002). For the cubes, the compression load will be applied to the face with a nominal area of 50x50mm cubes. The compressive strength of the cubes will be determined by dividing the maximum load by the load area of the specimen.

Calculate the compressive strength Cs in megapascals from equation 4.1:

$$\mathbf{Cs = P / 2500} \qquad \text{Equation 4.1}$$

Where

Cs is the compressive strength, in megapascals;

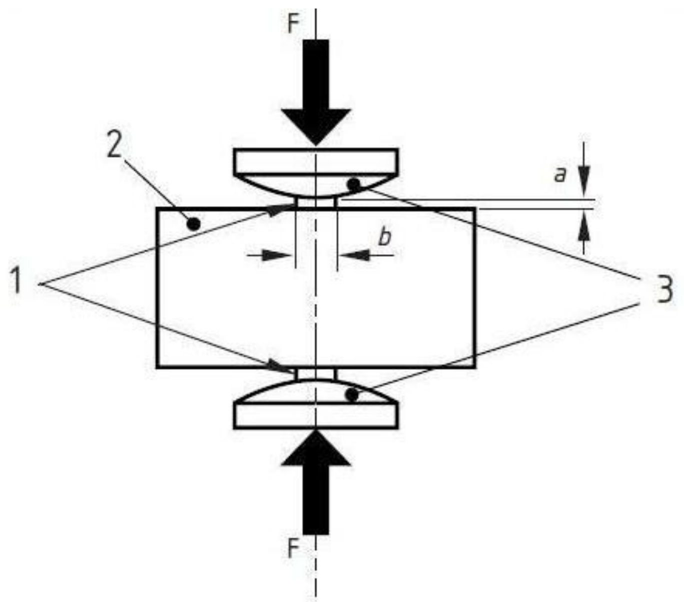
P is the failure load, in newtons;

2500 is the area of the cubes (50x50mm), in square millimetres.

4.2 Measurement of split tensile strength test

The split tensile strength of paving blocks was determined in accordance with BS EN1338: 2003. Before the blocks were tested, any burrs or high spots present on the block were removed. Next, the blocks were immersed in water at 20 (± 5) °C for a specified period of time (24 ± 3 hours). Once they were removed from the water, they were wiped dry and tested immediately.

The longest splitting section of the block specimen was tested. Before the test, the block specimen was placed in the split tensile test steel frame with the concentric wood packing pieces on the top and bottom of the specimens as shown in Figure 4.1.



1 Packing pieces
2 Paving block
3 Rigid bearers

a (4 ± 1) mm thick and at least 10 mm longer than the anticipated fracture plane.
b The two packing pieces (15 ± 1) mm wide.

Figure 4.1: Principle of split tensile strength test

The platens of the loading machine were in constant contact with the top and bottom steel plates of the testing frame. The load was slowly applied at a rate of 0.05 (± 0.01) MPa/s with a loading rate of 1.217 kN/s for blocks with a thickness of 80mm until failure was reached, when the specimen split into two halves the test was terminated. The failure load was recorded and the split tensile strength, in MPa, was calculated using the results of the failure load by using a formula and a correction factor according to BS EN 1338: 2003. The British standard BS EN1338: 2003 recommends that a minimum split tensile strength of 3.6 MPa must be obtained for all paving blocks.

Calculate the area of the failure plane of the block tested from the equation 4.2:

$$\mathbf{S = l \times t} \qquad \text{Equation 4.2 (BS EN1338: 2003).}$$

Where

S is the area of the failure, in square millimetres;

l is the failure length of the block, in millimetres;

t is the thickness of the block at the failure plane in millimetres.

Calculate the split tensile strength T in megapascal of the block tested from the equation 4.3:

$$\mathbf{T = 0.637 \times K \times \frac{F}{S}} \qquad \text{Equation 4.3 (BS EN1338: 2003).}$$

Where

T is the split tensile strength, in megapascals;

F is the failure load, in newtons;

K is a correction factor for the block thickness calculated by the equation 4.4.

S is area of the failure plane.

$\mathbf{K = 1.3 - 30\ (0.18 - t / 1000)^2}$ if 140 mm < t ≤ 180 mm Equation 4.4 (BS EN1338: 2003).

Or:

K = 1.3 if t > 180 mm

For t ≤ 140 mm determined from table 4.1.

Table 4.1: correction factor K (BS EN1338: 2003)

T (mm)	40	50	60	70	80	90	100	110	120	130	140
K	0.71	0.79	0.87	0.94	1.00	1.06	1.11	1.15	1.19	1.23	1.25

The mean strength must be at least 3.6 MPa with no individual result below 2.9 MPa.

4.3 Slip/Skid resistance

Skid resistance is the ability to resist relative movement between a vehicle tyre and the concrete paving block surface. On the other hand, slip resistance is the ability to resist relative movement between a pedestrian foot and the concrete paving blocks surface. The capacity of concrete paving blocks once it is laid and in use to decrease the likelihood of pedestrians slipping and vehicles skidding is measured by determining its slip/skid resistance. In order to measure unpolished slip resistance use is made of a standard rubber material which is attached to a pendulum friction tester; this was tested under wet conditions. BS EN1338: 2003 was used in order to establish the polished paver value (PPV).

The measurement of USRV (unpolished slip resistance value) on the specimen is made using the pendulum friction test equipment to evaluate the frictional properties of the specimen on the upper face. The pendulum friction test equipment incorporates a spring loaded slider made of a standard rubber attached to the end of the pendulum. On swinging the pendulum the frictional force between the slider and test surface is measured by the reduction in length of the swing using a calibrated scale.

The method used in this test is able to measure under laboratory conditions paving block's slip resistance subsequent to its having been synthetically trafficked in order to reproduce the way that paving blocks will perform across its lifetime under traffic conditions. If the surface of paving blocks contains ridges, grooves or other surface features which prevent testing by the pendulum friction equipment, the product is deemed to satisfy the requirements of this standard without testing.

Procedure of the test is by keeping the friction test equipment, and slider, in a room at a temperature of (20 ± 2) °C for at least 30 minute before the test begins. Immediately prior to testing with the friction tester, immerse the sample in water at (20 ± 2) °C for at least 30 minute. Place the friction tester upon a firm level surface and adjust the levelling screws so that the pendulum support column is vertical. Then raise the axis of suspension of the pendulum so that the arm swings freely, and adjust the friction in the pointer mechanism so that when the pendulum arm and pointer are released from the right-hand horizontal position the pointer comes to rest at the zero position on the test scale.

Rigidly locate the test specimen with its longer dimension lying in the track of the pendulum, and centrally with respect to the rubber slider and to the axis of the suspension of the pendulum. Ensure that the track of the slider is parallel to the long axis of the specimen across the sliding distance. Adjust the height of the pendulum arm so that in traversing the specimen the rubber slider is in contact with it over the whole width of the slider and over the specified swept length. Wet the surfaces of the specimen and the rubber slider with a copious supply of water, being careful not to disturb the slider from its set position. Release the pendulum and pointer from the horizontal position; catch the pendulum arm on its return swing. Record the position of the pointer on the scale (the pendulum test value). Perform this operation five times, rewetting the specimen each time, and record the mean of the last three readings.

The pendulum friction test shown in Figure 4.2

Figure 4.2: The pendulum friction tester used in the slip/skid resistance test

The following slip resistance table 4.2 gives an indication of the value against the potential for slip.

Table 4.2: Pendulum test values (BS EN1338: 2003)

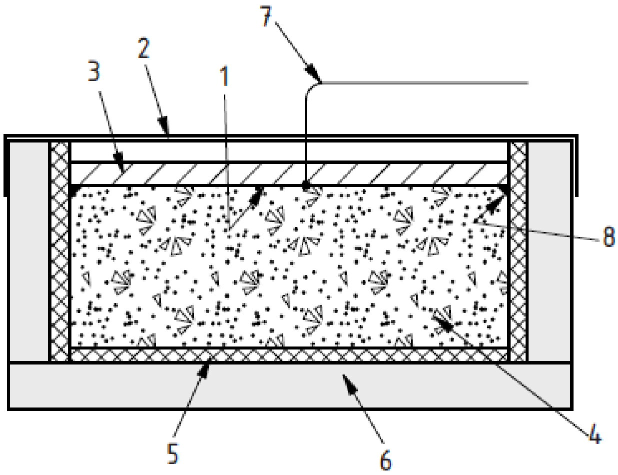
Pendulum test value	Potential for slip	Description of surface
Below 19	High	Dangerous
20 to 39	Moderate	Marginal
40 to 74	Low	Satisfactory
Above 75	Extremely low	Excellent

4.4 Weathering resistance

This is an expression of the extent to which concrete paving block is able to withstand weathering where particular circumstances exist, such as surfaces being frequently subjected to contact with de-icing salt when there is frost. It is possible to assess this capacity under laboratory conditions by making a measurement of the amount of spalled material accumulating on a surface when it has been subjected to repeated freezing and thawing with a de-icing salt being used. Where there has been no use of de-icing salt, measurements should be made of the porosity by measuring the block's water absorption.

4.4.1 Determination of freeze/thaw resistance with de-icing salt

Before specimens were tested, they had to be primed; specimens being tested had to be at least 28 days old and not more than 35 days old, any loose material or flashings had to be removed beforehand. The samples were then cured for 168 (±5) hours in a climate chamber with the temperature set at 20 (±2) °C and relative humidity set at 65 (±10) %, a minimal 50mm air space was also left between samples. The rubber sheet was glued to all surfaces of the specimen apart from the test surface and remains glued throughout the test. Silicon rubber or other sealants were used to fill in any chamfers around the perimeter of the specimen; the rubber provides a seal around the test surface. Water penetration is avoided as a seal is created in the corners between the concrete and the rubber sheet. The edge of the rubber sheet should reach 20 (± 2) mm above the test surface. Once specimens have been cured in the climate chamber, potable water at a temperature of 20 (± 2) °C is then poured onto the test surface until a depth of 5 (± 2) mm is reached. This depth is maintained for 72 (± 2) hours at 20 (± 2) °C and used to assess the effectiveness of the seal between the specimen and the rubber sheet. Before freeze/thaw cycling commences, all specimen surfaces, apart from the test surface, is thermally insulated as shown in figure 4.3.



Key

1 Test surface	5 Rubber sheet
2 Polyethylene sheet	6 Thermal insulation
3 Salted water	7 Temperature measuring device
4 Specimen	8 Sealant string

Figure 4.3: Principle of set-up used for the freeze/thaw test

Test procedure, 15 to 30 minute before the specimens are placed in the freezing chamber, the water on the test surface shall be replaced with a (5 ± 2) mm layer, measured from the top surface of the specimen, of 3 % NaCl in potable water. Specimens were placed in freezing chambers and ensured that test surfaces do not deviate from a horizontal plane by more than 3 millimetres per metre in any direction, next they were subjected to repeated freezing and thawing. The temperature is exceeded during each cycle which lasts about 7 to 9 hours.

The break points are given in table 4.3.

Table 4.3: Co-ordinates of break points

Upper limit		Lower limit	
Time (h)	Temp. (C°)	Time (h)	Temp. (C°)
0	24	0	16
5	-2	3	-4
12	-14	12	-20
16	-16	16	-20
18	0	20	0
22	24	24	16

In this investigation, the upper limit of temperature cycles was used.

After the 7th and 14th cycle, during the thaw period, if necessary to keep a 5 (± 2) mm layer, 3% NaCl dissolved in potable water was added. Once each specimen has undergone 28 cycles, the material was collected from the test surface. Specimens were rinsed into a vessel by using a spray bottle and the material was brushed into the vessel until no more material can be removed. Next, the liquid and scaled material were carefully poured through a filter paper and washed with at least 1 litre potable water; this removed any remaining NaCl. The filter paper and collected material are then dried for at least 24 hours at 105 (± 5) °C and the dry mass of the scaled material is determined to the nearest 0.2g.

Calculate the mass loss per unit area of the specimen (L) in kilograms per square metre from the equation 4.5:

$$\mathbf{L = \frac{M}{A}}$$ Equation 4.5 (BS EN1338: 2003).

Where

M is the mass of the total quantity of material scaled after 28 cycles, in kilograms;

A is the area of the test surface in square metres.

The British standard BS EN1338:2003 states that the mass loss after the freeze/thaw cycle test must be less than 1kg per metre squared.

4.4.2 Determination of total water absorption

Before the specimens were tested, any loose material or flashings had to be removed beforehand with a brush. Also, all specimens had to be at 20 (± 5) °C. Next, specimens are immersed, using the vessel in potable water at 20 (± 5) °C until constant mass M_1 is reached. Specimens are then separated from each other by ensuring that a minimal 15mm gap is left between each specimen and 20mm of water is above each specimen. The specimens are then kept in the water for at least 3 days.

The mass is recorded and the constant mass is attained when two weighting's, performed at a 24 hours interval show a 0.1% difference in mass. Before specimens are weighed, they are dried with a moistened cloth; specimens have been correctly dried when the surface of the concrete is dull. Next, each specimen is placed in an oven spaced at least 15mm apart from other specimens. The specimens are dried at 105 (± 5) °C until constant mass M_2 has been reached. Again, specimens are dried for at least three days and the constant mass is attained when two weighting's, performed at a 24 hours interval show a 0.1% difference in mass. Specimens must be cooled to room temperature before they are weighed.

Calculate the water absorption (W_a) of each specimen as a percentage of its mass from the equation 4.6:

$$\mathbf{W_a} = \frac{\mathbf{M_1} - \mathbf{M_2}}{\mathbf{M_2}} \times \mathbf{100}\ \%$$ Equation 4.6 (BS EN1338: 2003).

Where

M_1 is the initial mass of the specimen (g);

M_2 is the final mass of the specimen (g).

The British standard BS EN1338:2003 requires water absorption (W_a) $\leq$ 6.0.

5. Experimental program

The paving blocks are made by providing a high level of compaction through the use of hydraulic compaction pressure and high intensity vibration to the tray moulds in the factory. In this chapter the initial experiments were focused on the simulation of the factory compaction energy in the laboratory casting and the best way to achieve good consistent test results for paving blocks made in the laboratory. Then the factory mix design and materials were obtained and cast and tested in the laboratory, and the results were compared to the results obtained by the factory on the same tray specimens.

The acronyms used in this chapter are shown in the Table 5.1 below.

Table 5.1: Acronyms used

Ordinary Portland cement	OPC
Basic oxygen slag	BOS
Plasterboard gypsum	PG
Run-of-station ash	ROSA
Ground granulated blast furnace slag	GGBS
Cement by pass dust	BPD
Compressive strength	CS
Split tensile strength	TS

5.1 Summary of laboratory compaction simulation with factory

Different methods of compactions were examined; the first method used was rammer application to compact the materials in the mould, having divided it into three equal volume layers to ensure all of them were subjected to the same compaction energy.

There are a number of disadvantages to this method such as the power of compaction will depend on human muscle strength so that there is no way to achieve the same compaction in the three layers. This caused a wide spread of results for paving block samples as shown in Table 5.2. Furthermore, the last layer presents a particular problem when it is compacted, as there is some material over spill and therefore it is necessary to add more materials.

Table 5.2: The first compaction method average results i.e. rammer application to compact the materials in the mould

Mix code		Type	Age (days)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC40/GGBS30/ BOS30							
OPC	40%	Blocks	14	3.157	41.87	2160	1.81
GGBS	30%						
BOS	30%						
W/B	0.15						

The second method of compaction used was a hammer drill compaction technique. The compaction was done in three layers to give the same pressure or compaction energy, however the results were not satisfactory and gave wide variations in the density between specimens as shown in Table 5.3. This was due to the limited power of the drill.

Table 5.3: The second compaction method results i.e. hammer drill compaction technique to compact the materials in the mould

Mix code OPC40/GGBS30/BOS30		Type	Age (days)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC	40%	Blocks	14	2.750	30.07	1890	1.30
GGBS	30%						
BOS	30%						
W/B	0.15						

The third method of compaction used was a vibrating table (from the concrete V-B standard workability test apparatus). In this technique, the materials were placed in one layer and compacted by a drill hammer and the vibration of the base as shown in Table 5.4. Furthermore a mould collar was used to keep the materials placed in the mould. However, this technique also suffered from the limited power of the drill hammer and the vibrating table.

Table 5.4: The third compaction method results i.e. hammer drill compaction technique with vibrating table

Mix code OPC40/GGBS30/BOS30		Type	Age (days)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC	40%	Blocks	14	2.760	30.99	1890	1.34
GGBS	30%						
BOS	30%						
W/B	0.15						

Finally, the last method of compaction examined was a pressing action method by making use of a compression machine as shown in Figure 5.1.

Figure 5.1: Compression machine

In this technique, different magnitudes of loads were applied to determine the best results in order to obtain consistent density and optimum split tensile strength results. In this method, the materials were compacted in one layer. A mould collar was also used to retain the material within the mould.

Table 5.5 shows the results of compression compaction. The compaction loadings of 15, 20, 25, 30, 40, 70, 100, 150, 200,250 and 400 kN were tried and tested. The results indicated that over 70 kN loading gave more consistent results. 150 kN was adopted as the most practical load for the paste mixes as the bracing of the mould was not needed. However, in later research work on the concrete paving block mixes, 400 kN load was used to get comparable values of strength with factories. The 400 kN load required further bracing of the moulds to avoid the buckling of them. It can be seen in Table 5.5 the pressing action gave the best results and as the density measured showed close similarity with the factory specimens, therefore 150 and 400 kN loadings were adopted for casting of paste and concrete paving block specimens respectively.

Table 5.5: The pressing action technique results (using compression machine)

Mix code OPC40/GGBS30/ BOS30		Type	Age (days)	Pressing load (kN)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC	40%	Blocks	14	15	2.673	53.20	1833	2.3
				20	2.737	55.52	1877	2.4
				25	2.730	57.83	1872	2.5
GGBS	30%			30	2.911	64.77	1996	2.8
				40	2.931	67.08	2010	2.9
				70	2.975	71.71	2030	3.1
BOS	30%			100	3.138	76.33	2009	3.3
				150	3.175	87.89	2162	3.8
				200	3.173	90.21	2176	3.9
W/B	0.15			250	3.270	92.53	2242	4.0
				400	3.262	129.54	2236	5.6

The average results of three paste specimens prepared using compression machine technique are shown in Figure 5.2.

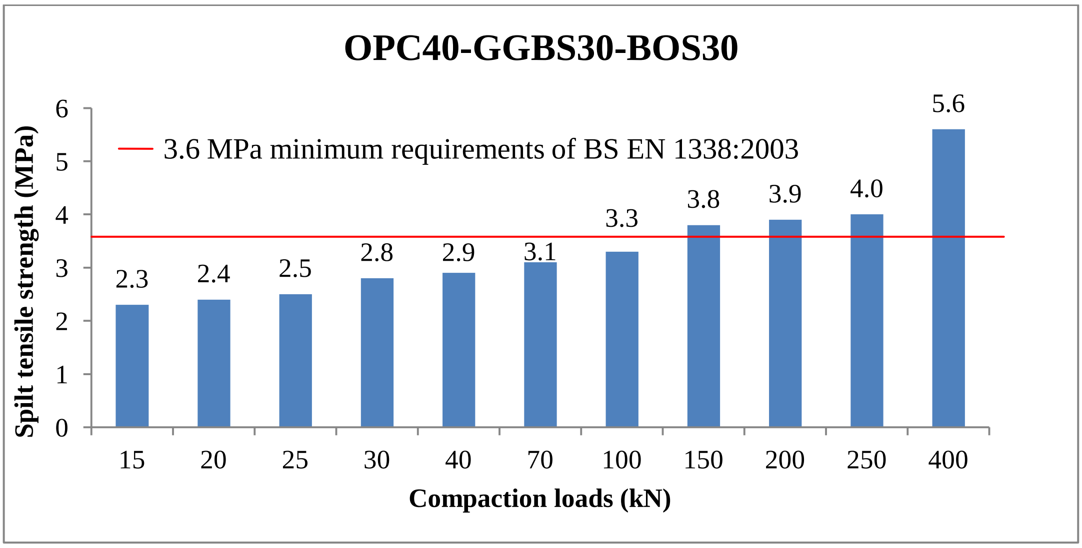


Figure 5.2: The split tensile strength in (MPa) of OPC40-GGBS30-BOS30 after 14 days under different pressing loads in (kN)

As expected, 400 kN gave the highest strength. Loadings of more than 400 kN was not required since the similar density compared to the factory paving blocks was obtained and the bracing of the moulds would have proved difficult. Another concern for higher compaction loadings above 400 kN was the crushing of the aggregates in concrete paving blocks.

Figure 5.3 shows the effect of different compaction loadings on the split tensile strength of the paste and the pressing action gives the highest split tensile strength for the paste compared to other methods.

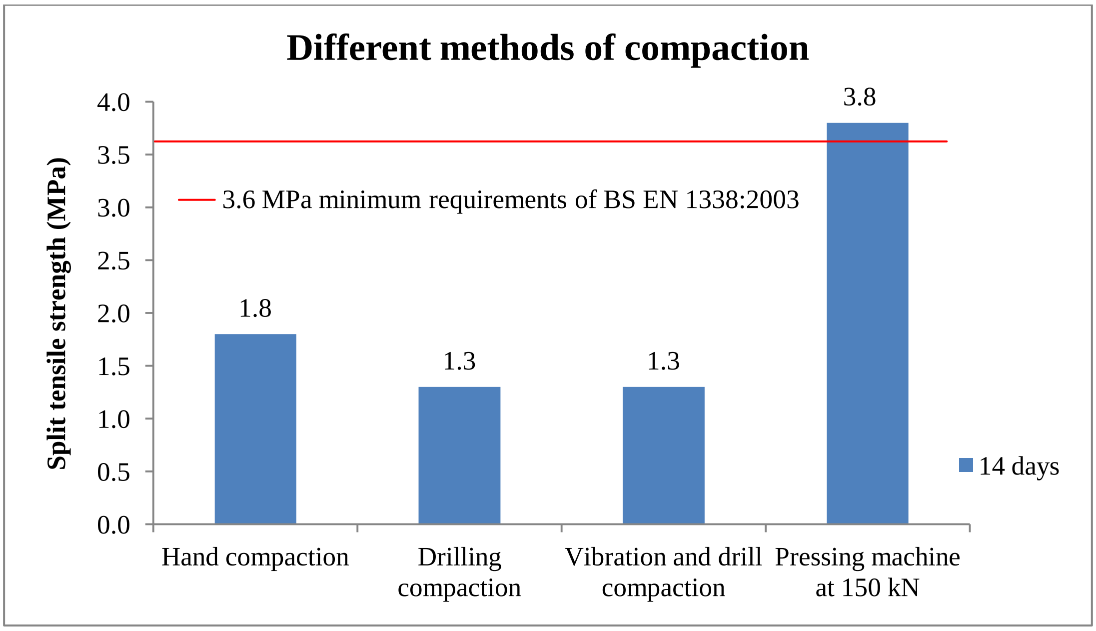


Figure 5.3: The split tensile strength test in (MPa) of OPC40-GGBS30-BOS30 after 14 days with different method of compaction used

5.2 Experimental phases

The aim of this research was to determine the best way to achieve good and consistent test results in the laboratory for paving blocks. A compression machine was used for a pressing action. The aim was to achieve the greatest split tensile strength for both binary and tertiary mixtures.

In the first phase, paste mixes using five different combinations of raw materials were designed and used for both paving blocks and cube specimens; they were then tested for both compressive and split tensile strength. For all groups in the first phase as paste mixes the water content was 15 percent as shown in Table 5.6.

The second phase of this study was to select the best results between all paste mixes from the first phase and using virgin coarse aggregates 4mm and 6mm which are similar to the mix design used by factories as shown in Table 8.2. The third phase of the study was to select the best mix from the second phase to satisfy the requirements of the BS EN 1338:2003 standard and completely replace 4mm and 6mm virgin aggregates with waste recycled materials as shown in Table 8.5. Concrete paving blocks were tested for split tensile strength and compressive strength at 14 and 28 days, slip/skid resistance (BPN), weathering resistance and density.

5.3 Casting and curing

Paving blocks were made with 190x100 mm cross section and three different thickness sizes these were 76 mm (I), 80 mm (II) and 75 mm (III).

The cube size was 50 mm. A compression machine was used to fully compact the materials in one layer with 150 kN of load on the blocks and 19.74 kN on the cubes with stress at 7.9 MPa for the first phase, and 400 kN of load was used on the blocks and 52.63 kN on the cubes with stress at 21.1 MPa for the second and third phase.

Once cast the specimens were covered with a polythene sheet so that there would be no loss of water. On the next day all samples were de-moulded and then stored in curing chambers at a constant air temperature of 22$\pm$2°C degrees C and 98% relative humidity until they were to be tested as detailed in chapter 4.

5.4 Mix designs, results and discussion

5.4.1 Mix designs for paste paving blocks (first phase)

The mix design of all paste made are shown in Table 5.6. Ten different groups of paste blocks were made.

Table 5.6: Mixes proportions of paving blocks without aggregates; first phase (mix proportions given as percentage by weight)

Mix code	OPC (%)	ROSA (%)	GGBS (%)	BOS (%)	PG (%)	BPD (%)	W/B
OPC70/ROSA30	70	30	-	-	-	-	0.15
OPC60/ROSA40	60	40	-	-	-	-	0.15
OPC50/ROSA50	50	50	-	-	-	-	0.15
OPC40/ROSA60	40	60	-	-	-	-	0.15
OPC30/ROSA70	30	70	-	-	-	-	0.15
OPC40/GGBS30/BOS30	40	-	30	30	-	-	0.15
OPC30/GGBS40/BOS30	30	-	40	30	-	-	0.15
OPC30/GGBS30/BOS40	30	-	30	40	-	-	0.15
OPC30/GGBS35/BOS35	30	-	35	35	-	-	0.15
OPC20/GGBS40/BOS40	20	-	40	40	-	-	0.15
OPC20/GGBS30/BOS50	20	-	30	50	-	-	0.15
OPC70/BOS25/PG5	70	-	-	25	5	-	0.15
OPC60/BOS35/PG5	60	-	-	35	5	-	0.15
OPC50/BOS45/PG5	50	-	-	45	5	-	0.15
OPC50/BOS47/PG3	50	-	-	47	3	-	0.15
OPC50/BOS30/PG20	50	-	-	30	20	-	0.15
OPC40/BOS55/PG5	40	-	-	55	5	-	0.15
OPC30/BOS65/PG5	30	-	-	65	5	-	0.15
OPC30/BOS25/PG45	30	-	-	25	45	-	0.15
OPC30/BOS55/PG15	30	-	-	55	15	-	0.15
OPC30/ROSA35/BOS35	30	35	-	35	-	-	0.15
OPC40/ROSA30/BOS30	40	30	-	30	-	-	0.15
OPC50/ROSA25/BOS25	50	25	-	25	-	-	0.15
OPC50/ROSA20/BOS30	50	20	-	30	-	-	0.15
OPC52/ROSA30/BOS18	52	30	-	18	-	-	0.15
OPC60/ROSA20/BOS20	60	20	-	20	-	-	0.15
OPC70/ROSA15/BOS15	70	15	-	15	-	-	0.15

Table 5.6- continue.

Table 5.6: Continued

Mix code	OPC (%)	ROSA (%)	GGBS (%)	BOS (%)	PG (%)	BPD (%)	W/B
OPC40/ROSA55/PG5	40	55	-	-	5	-	0.15
OPC50/ROSA45/PG5	50	45	-	-	5	-	0.15
OPC60/ROSA35/PG5	60	35	-	-	5	-	0.15
OPC70/ROSA25/PG5	70	25	-	-	5	-	0.15
OPC70/ROSA27/PG3	70	27	-	-	3	-	0.15
OPC80/ROSA15/PG5	80	15	-	-	5	-	0.15
OPC80/ROSA17/PG3	80	17	-	-	3	-	0.15
OPC70/BOS30	70	-	-	30	-	-	0.15
OPC60/BOS40	60	-	-	40	-	-	0.15
OPC50/BOS50	50	-	-	50	-	-	0.15
OPC40/BOS60	40	-	-	60	-	-	0.15
OPC30/BOS70	30	-	-	70	-	-	0.15
OPC80/GGBS15/PG5	80	-	15	-	5	-	0.15
OPC70/GGBS25/PG5	70	-	25	-	5	-	0.15
OPC60/GGBS35/PG5	60	-	35	-	5	-	0.15
OPC60/GGBS20/PG20	60	-	20	-	20	-	0.15
OPC50/GGBS45/PG5	50	-	45	-	5	-	0.15
OPC50/GGBS47/PG3	50	-	47	-	3	-	0.15
OPC40/GGBS55/PG5	40	-	55	-	5	-	0.15
OPC40/GGBS15/PG45	40	-	15	-	45	-	0.15
OPC40/GGBS45/PG15	40	-	45	-	15	-	0.15
OPC70/ROSA20/BPD10	70	20	-	-	-	10	0.15
OPC60/ROSA25/BPD15	60	25	-	-	-	15	0.15
OPC50/ROSA30/BPD20	50	30	-	-	-	20	0.15
OPC50/ROSA40/BPD10	50	40	-	-	-	25	0.15
OPC40/ROSA35/BPD25	40	35	-	-	-	30	0.15
OPC40/ROSA40/BPD20	40	40	-	-	-	20	0.15
OPC30/ROSA40/BPD30	30	40	-	-	-	10	0.15
OPC30/ROSA60/BPD10	30	60	-	-	-	10	0.15
OPC75/GGBS20/BPD5	75	-	20	-	-	5	0.15
OPC70/GGBS20/BPD10	70	-	20	-	-	10	0.15
OPC60/GGBS30/BPD10	60	-	30	-	-	10	0.15
OPC50/GGBS40/BPD10	50	-	40	-	-	10	0.15
OPC50/GGBS45/BPD5	50	-	45	-	-	5	0.15
OPC50/GGBS30/BPD20	50	-	30	-	-	20	0.15
OPC40/GGBS55/BPD5	40	-	55	-	-	5	0.15
OPC40/GGBS20/BPD40	40	-	20	-	-	40	0.15
OPC80/BOS10/BPD10	80	-	-	15	-	10	0.15
OPC70/BOS20/BPD10	70	-	-	20	-	10	0.15
OPC60/BOS33/BPD7	60	-	-	33	-	7	0.15
OPC50/BOS45/BPD5	50	-	-	45	-	5	0.15
OPC40/BOS55/BPD5	40	-	-	55	-	5	0.15
OPC40/BOS10/BPD50	40	-	-	10	-	50	0.15
OPC40/BOS40/BPD20	40	-	-	40	-	20	0.15

5.4.2 Results and discussion for paste paving blocks (first phase)

Results of compressive strength and split tensile strengths of each group of mixtures are shown in figures 5.4 to 5.39.

5.4.2.1 Binary mixture of OPC-ROSA

In general, run-of-station ash (ROSA) showed satisfactory pozzolanic potential for use with basic oxygen slag, plasterboard gypsum and cement bypass dust. In addition, using binary and ternary mixtures OPC-ROSA, OPC-ROSA-BOS, OPC-ROSA-PG and OPC-ROSA-BPD showed adequate split tensile strength to satisfy the 3.6 (MPa) standard requirements.

From figures 5.4 and 5.5 it can be seen that the strength development of paste mixtures using a range of ROSA and OPC with W/B ratio 0.15 indicated that a mixture of 50 % ordinary Portland cement (OPC) and 50% run-of-station ash (ROSA) showed the highest compressive strength and split tensile strength at 28 days with 26.38 MPa and 5.42 MPa, respectively. This confirms that as the ROSA content increases the strength is reduced. This is due to the ash particles acting as filler without contribution to the gel formation in a cement paste matrix of the paste.

Moreover, compressive strength and split tensile strength were reduced as a result of increasing the ROSA content by more than 50%. In addition, mechanical properties of mixture containing 40% OPC and 60 % ROSA are still higher than the minimum requirement and 60% cement reduction was achieved in the mix design.

On the other hand, a mixture containing 30% OPC and 70 % ROSA proved the lowest compressive and split tensile strength at 28 days comparing with other mixes in the same group. The average ratio of compressive strength to split tensile strength in this group was 5.5.

The results of OPC-ROSA paste are shown in figure 5.4 and 5.5.

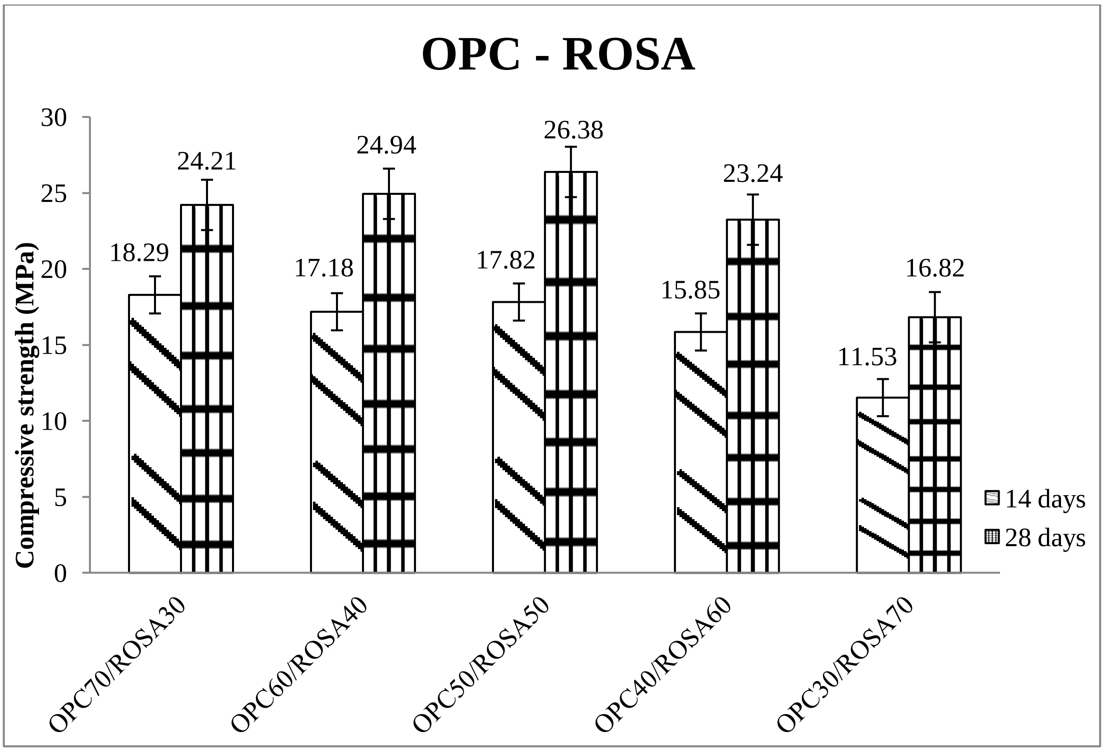


Figure 5.4: Compressive strength of 50x50mm cubes for OPC-ROSA after 14 & 28 days

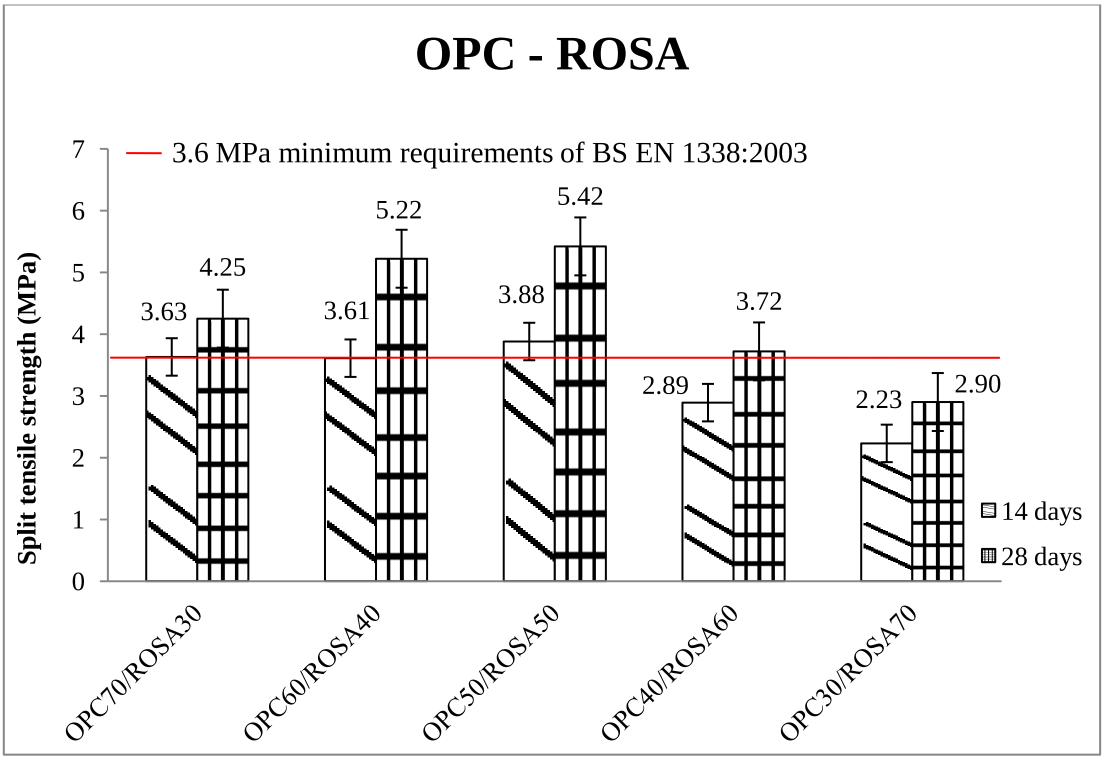


Figure 5.5: Split tensile strength of paving blocks for OPC-ROSA after 14 & 28 days

5.4.2.2 Ternary mixture of OPC-GGBS-BOS

The characteristic strength of paving blocks prepared with ternary mixture of OPC-GGBS-BOS showed higher split tensile strength result than the minimum required of 3.6 MPa after 28 days.

Furthermore, figure 5.8 shows that the use of up to 20 % ordinary Portland cement (OPC), 40% ground granulated blast furnance slag (GGBS) and 40% basic oxygen slag (BOS) as a replacement for cement results in sufficient results after 28 days in the split tensile strength, the results also confirmed that it is possible to reduce cement by up to 80%.

Moreover, it can be seen that the maximum compressive strength and split tensile strength can be achieved by using 20% OPC, 30% GGBS and 50% BOS and the strength at 28 days were 35.11MPa and 5.41MPa respectively. On the other hand, strength of all mixes in this group was higher than the minimum requirements of the British standard BS EN 1338:2003.

The results of OPC-GGBS-BOS paste are shown in figures 5.6 and 5.7.

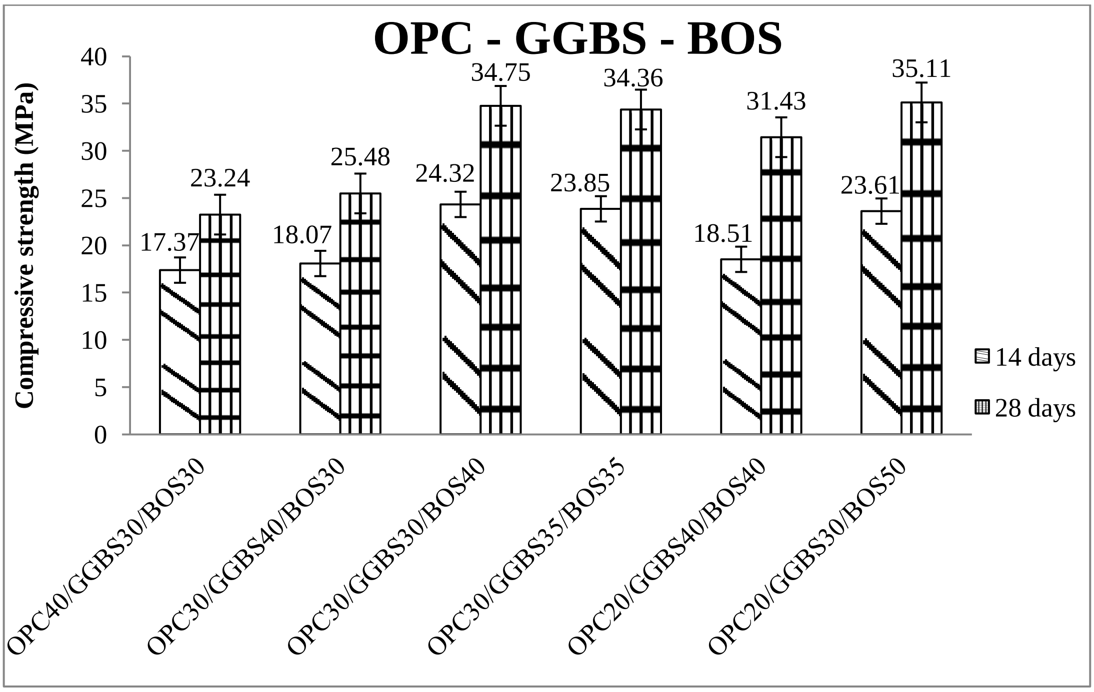


Figure 5.6: Compressive strength of 50x50mm cubes for OPC-GGBS-BOS after 14 & 28 days

Figure 5.7 shows that in OPC-GGBS- BOS mixes the effect of increase in OPC content is not considerable on compressive strength where OPC ranges from 20-30%; while GGBS showed beneficial effect within above range. However, this trend appears to be opposite in mixes where GGBS ranges from 30% to 40%.

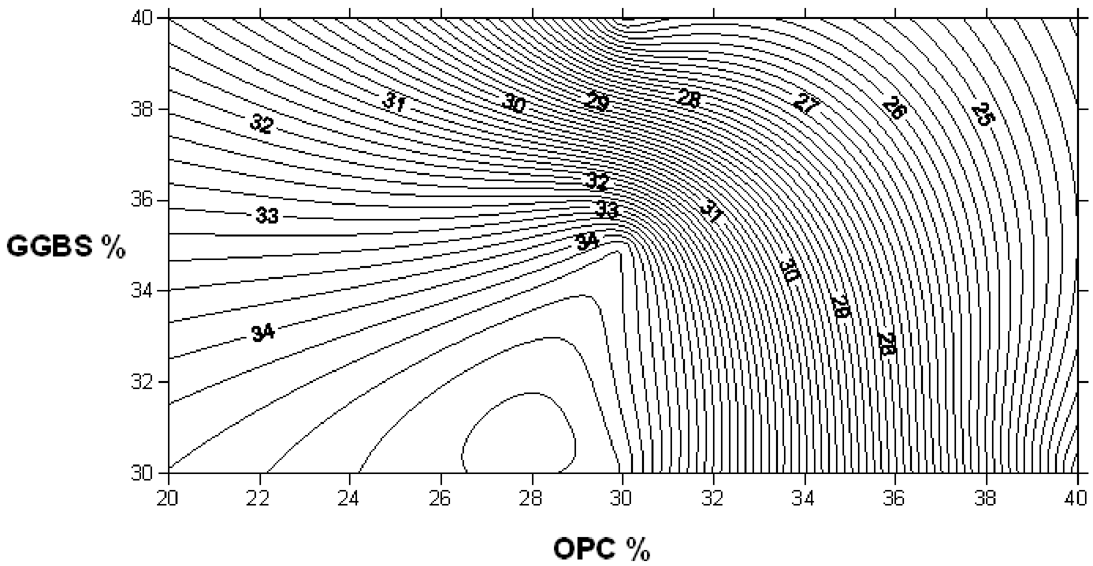


Figure 5.7: Compressive strength contours of 50x50mm cubes for OPC-GGBS-BOS after 28 days

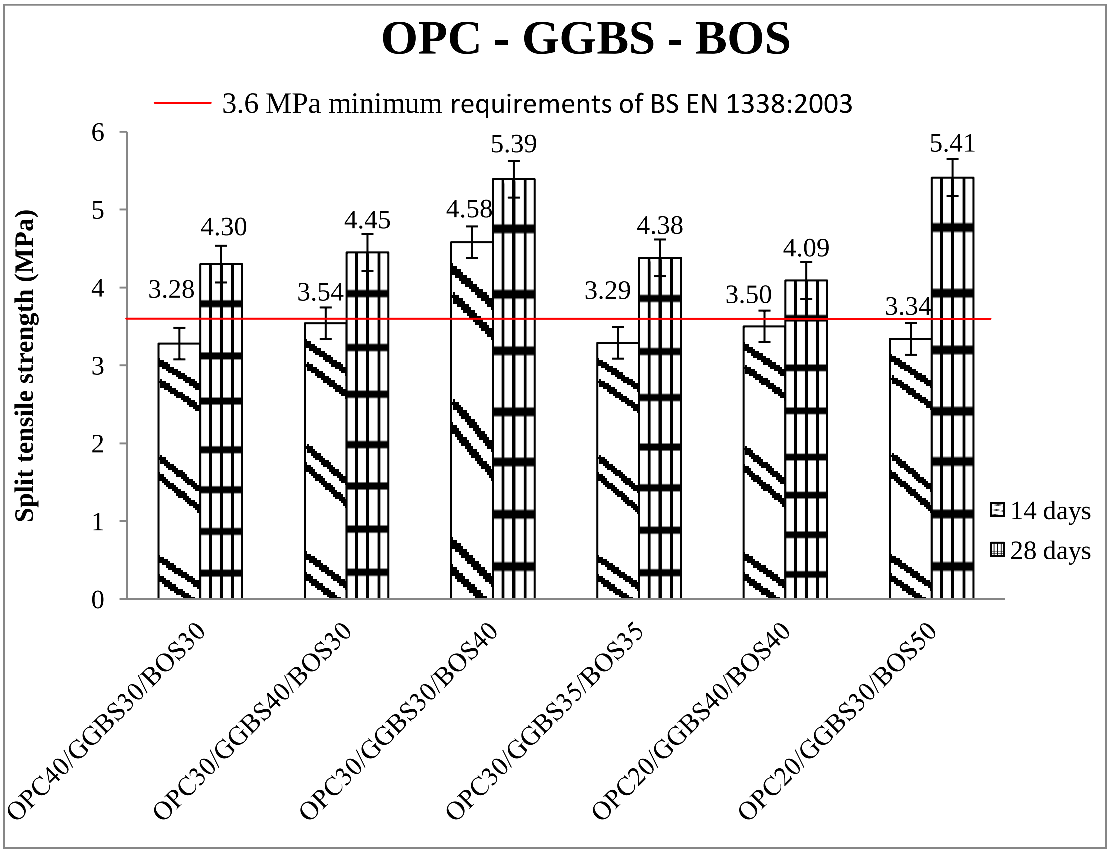


Figure 5.8: Split tensile strength of paving blocks for OPC-GGBS-BOS after 14 & 28 days

Figure 5.9 shows that in OPC-GGBS- BOS mixes the effect of increase in OPC content is significant on split tensile strength where OPC ranges from 20-30%; whereas the effect of GGBS content on split tensile strength appears to insignificant in range of GGBS 20-40%. The average ratio of compressive strength to split tensile strength in this group was 6.6.

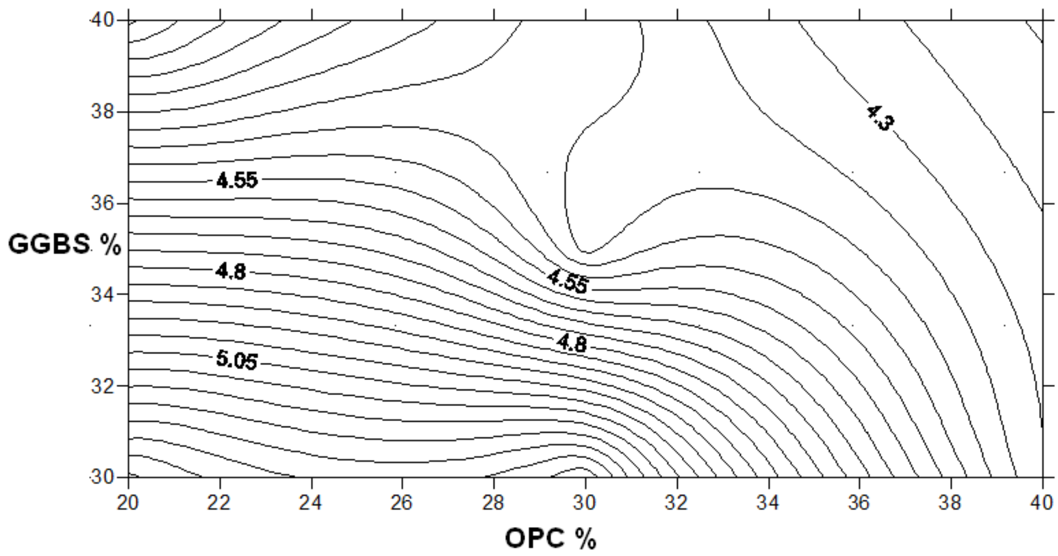


Figure 5.9: Split tensile strength contours of paving blocks for OPC-GGBS-BOS after 28 days

5.4.2.3 Ternary mixture of OPC-BOS-PG

The results of compressive strength and split tensile strength mixes prepared with ternary mixture of OPC, BOS and PG with W/B ratio 0.15 are shown in figures 5.10 to 5.13. As expected the compressive strength of the cubes specimens in this group showed the same trend as paving blocks specimens.

The results evidenced that mix 60 % ordinary Portland cement (OPC), 35% basic oxygen slag (BOS) and 5% plasterboard gypsum (PG) achieved the highest compressive and split tensile strength at 28 days with 40.76MPa and 5.09MPa correspondingly. Also, the results of mix containing OPC30-BOS65-PG5 show the possibility to reduce 70% of cement and the result of strength still higher than the minimum requirements. Nevertheless, results of this group confirmed that all mixes within 5% plasterboard gypsum were higher than 3.6 MPa in split tensile strength after 28 days according to the minimum requirements of the British standard BS EN 1338:2003. On other hand, increasing the percent of plasterboard gypsum more than 5% in combination with OPC-BOS-PG as a partial replacement of cement showed unsatisfactory results as shown in figure 5.12.

Dunster (2008) showed that the addition of gypsum at quantities greater than 5% SO3 (by weight of cement) to such cements (which contain calcium aluminate and calcium silicate hydrates) leads to a high risk of durability problems. This is because the excess sulphate reacts with the silicates and aluminates in the cement to form large amounts of expansive products, such as ettringite.

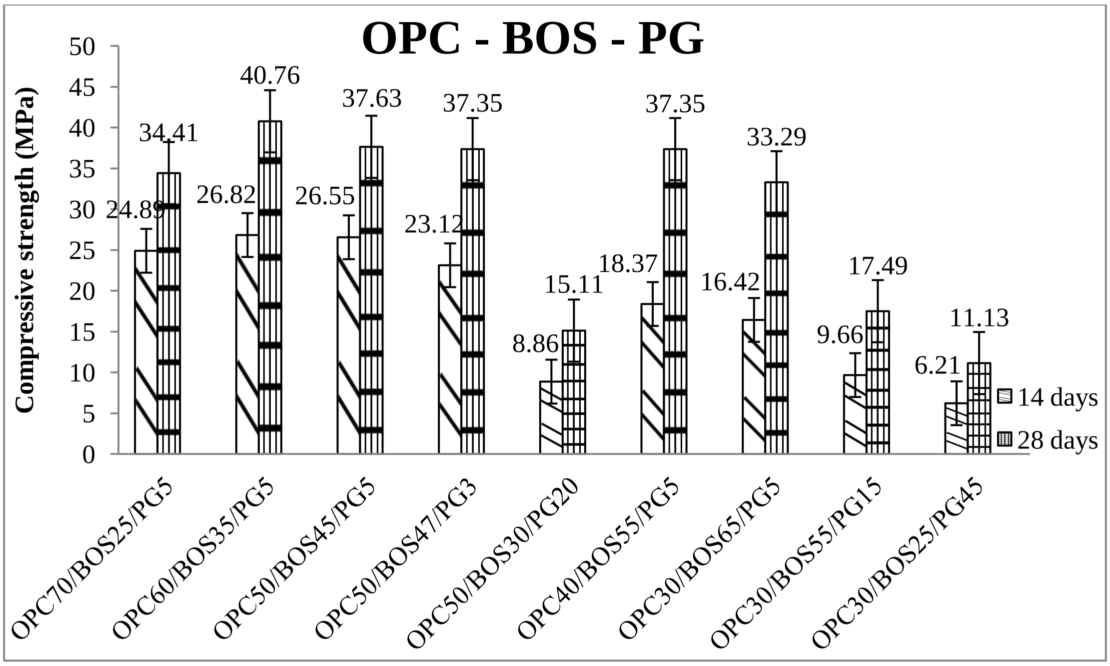


Figure 5.10: Compressive strength of 50x50mm cubes for OPC-BOS-PG after 14 & 28 days

Figure 5.11 shows that in OPC-BOS-PG mixes the effect of increase in OPC content is considerable in compressive strength where OPC ranges from 40-60%; while the effect of BOS showed the opposite trend within the ranges from 30-50%.

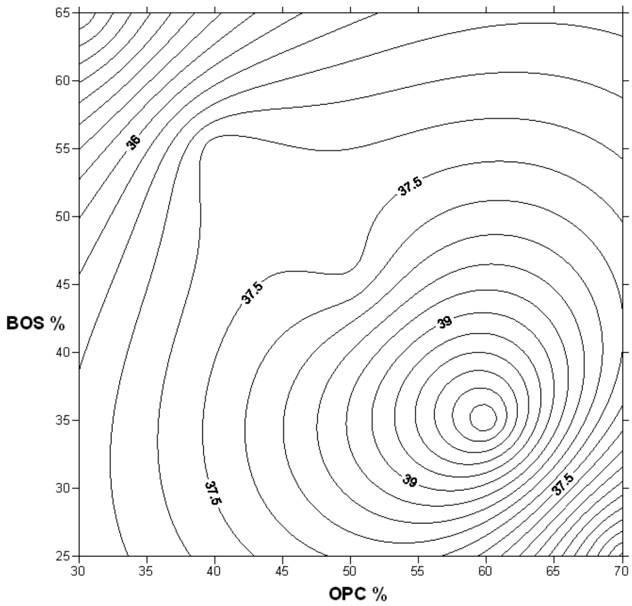


Figure 5.11: Compressive strength contours of 50x50mm cubes for OPC-BOS-PG after 28 days

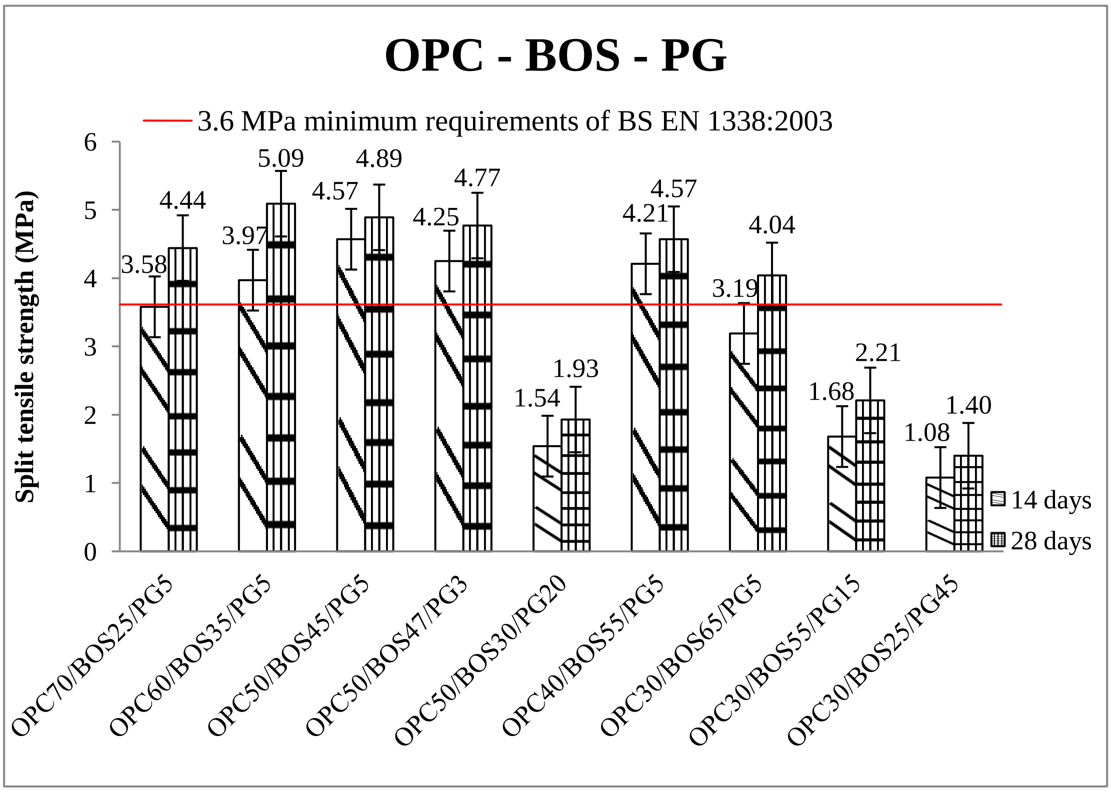


Figure5.12: Split tensile strength of paving blocks for OPC-BOS-PG after 14 & 28 days

Figure 5.13 shows that in OPC-BOS-PG mixes the effect of increase in OPC content is significant in split tensile strength where OPC ranges from 40-60%; however the effect of increase in BOS showed opposite trend within the ranges from 30-50%. It can be seen that as the BOS content increased to more than 35% the strength decreased. The average ratio of compressive strength to split tensile strength in this group was 7.9.

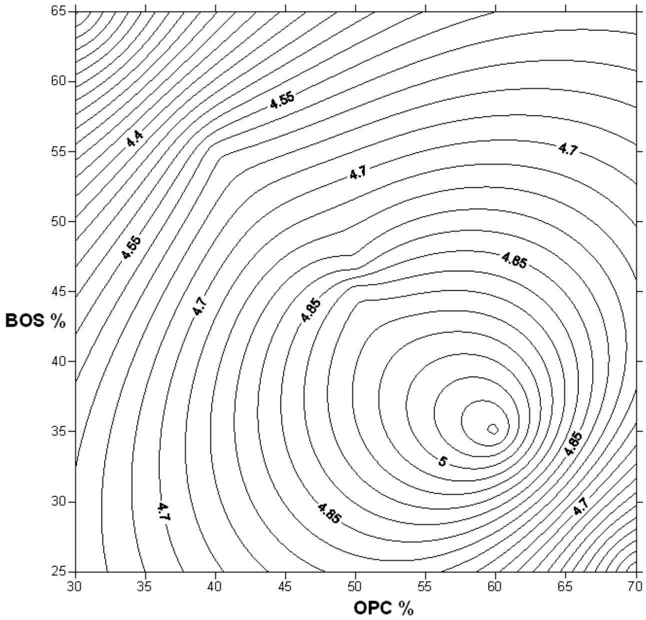


Figure 5.13: Split tensile strength contours of paving blocks for OPC-BOS-PG after 28 days by Surfer 8 software at 28 days

5.4.2.4 Ternary mixture of OPC-ROSA-BOS

The results of compressive strength and split tensile strength mixes combing ternary components OPC, ROSA and BOS paste with W/B ratio 0.15 are shown in figures from 5.14 to 5.17. The paving blocks prepared with ternary mixture of 52 % ordinary Portland cement (OPC), 30% Run-of-station ash (ROSA) and 18% basic oxygen slag (BOS) showed the highest strength in compressive strength with 41.80MPa and 5.14MPa in split tensile strength at 14 and 28 days in this group as shown in figures below. On the other hand, mix containing OPC30-ROSA35-BOS35 showed the lowest strength at 14 and 28 days compared with other mixes in the same group, and shows sufficient results even at 14 days in the split tensile strength and confirmed that it is possible to reduce cement by up to 70%. Furthermore mechanical properties of all mixes in this group at 28 days satisfied the minimum requirements of the British standard BS EN 1338:2003.

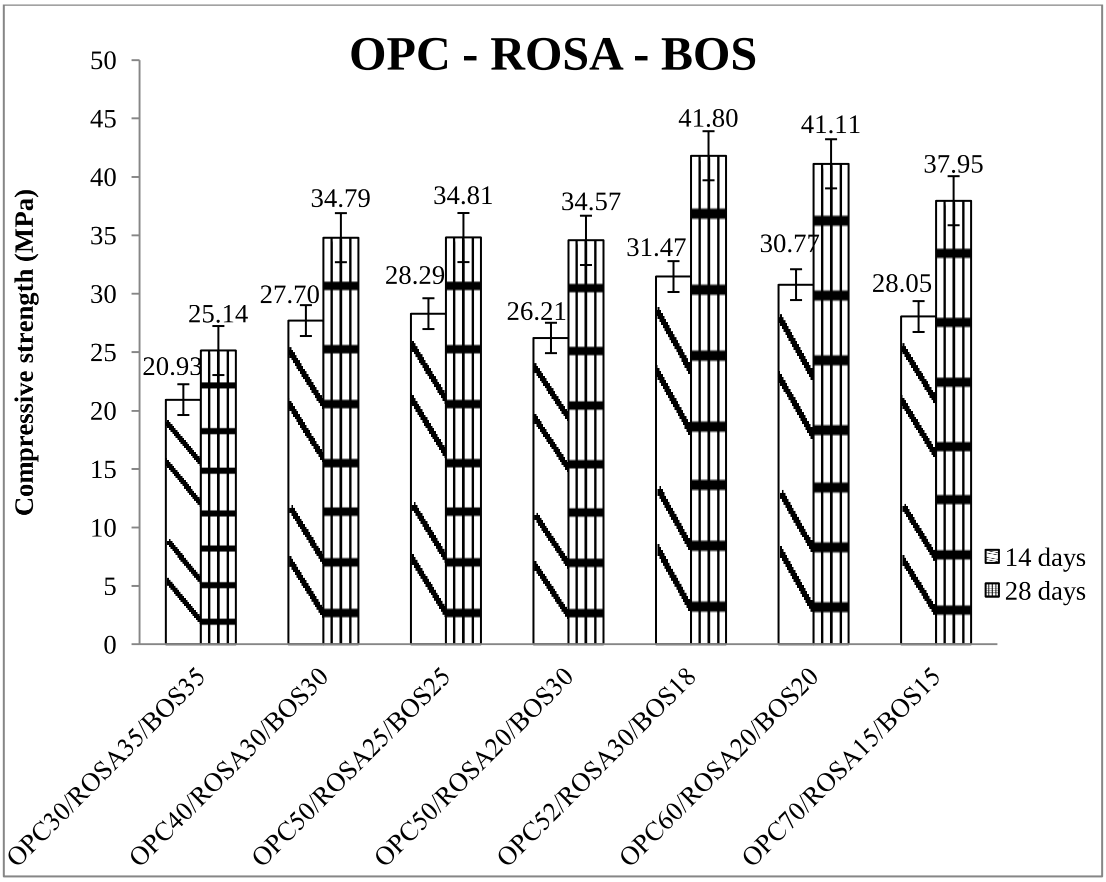


Figure 5.14: Compressive strength of 50x50mm cubes for OPC-ROSA-BOS after 14 & 28 days

Figure 5.15 shows that in OPC-ROSA-BOS mixes the result of increase in OPC content is considerable on compressive strength where OPC ranges from 30-60%; however increase in ROSA content showed the opposite trend within the range 15-35%.

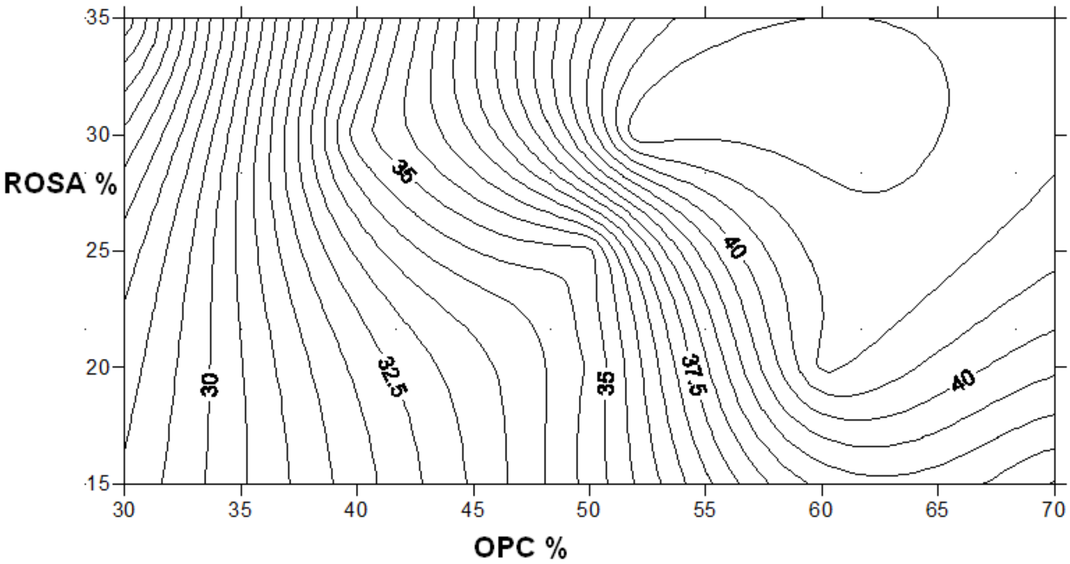


Figure 5.15: Compressive strength contours of 50x50mm cubes for OPC-ROSA-BOS after 28 days

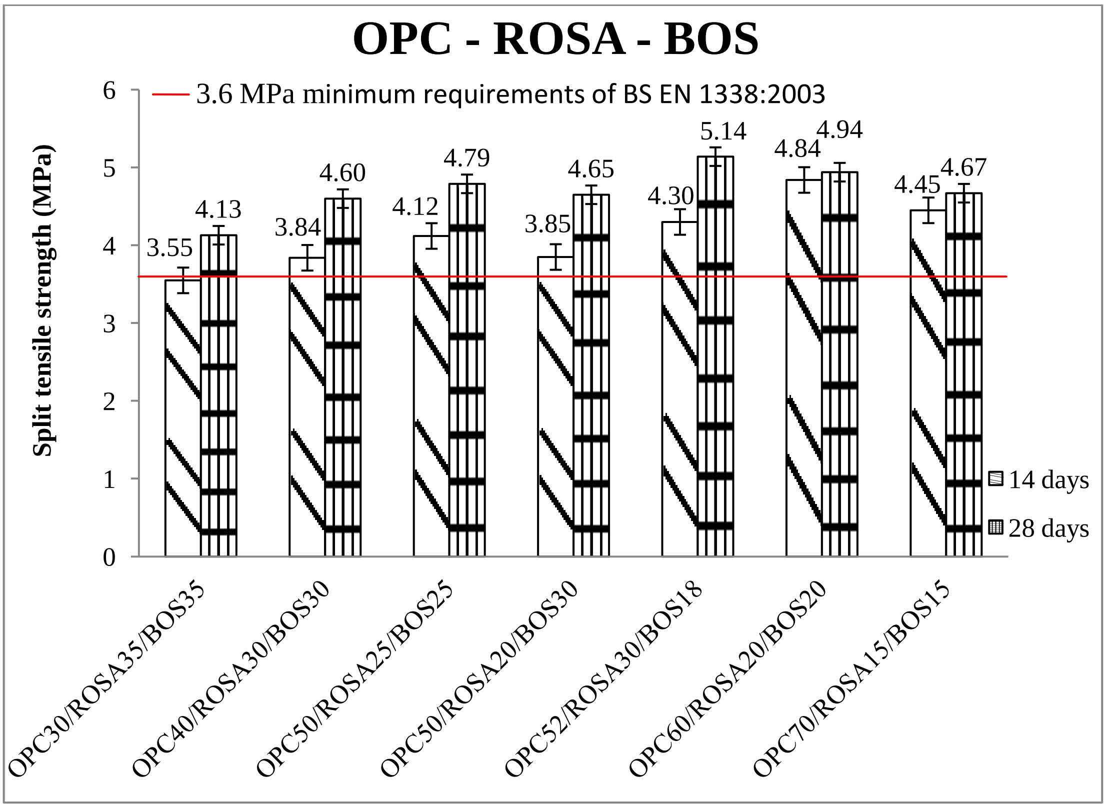


Figure 5.16: Split tensile strength of paving blocks for OPC-ROSA-BOS after 14 & 28 days

Figure 5.17 shows that in OPC-ROSA-BOS mixes the effect of increase in the OPC content is significant on split tensile strength where OPC ranges from 30-60%; on the other hand increase in ROSA content showed opposite trend within the range 15-30%. The average ratio of compressive strength to split tensile strength in this group was 7.6.

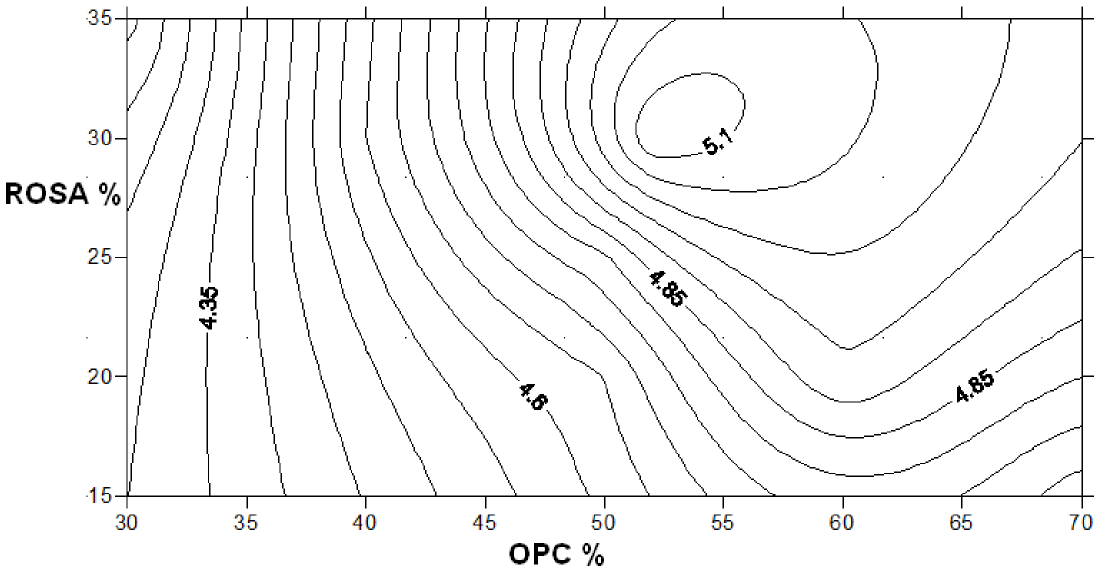


Figure 5.17: Split tensile strength contours of paving blocks for OPC-ROSA-BOS after 28 days

5.4.2.5 Ternary mixture of OPC-ROSA-PG

The results of compressive strength and split tensile strength ternary mixtures of OPC, ROSA and PG with W/B ratio 0.15 are shown in figures 5.18 to 5.21. The split tensile strength result of ternary mix containing 80 % ordinary Portland cement (OPC), 17% run-of-station ash (ROSA) and 3% plasterboard gypsum (PG) achieved the highest split tensile strength of 4.03 MPa in this group and meet the requirements of British standard BS EN 1338:2003 at 28 days, while the compressive strength was 32.11MPa after 28 days. Moreover, mix containing OPC70-ROSA27-PG3 shows satisfactory results at 28 days in the split tensile strength confirming that cement content can be reduced by up to 30%.

Furthermore, ternary mixes of OPC80-ROSA15-PG5 were also higher than 3.6 MPa according to the minimum requirements of the British standard BS EN 1338:2003 at 28 days. On the other hand, ternary mix containing OPC40-ROSA55-PG5 showed the lowest compressive and split tensile strength at 28 days comparing with other mixes in the same group.

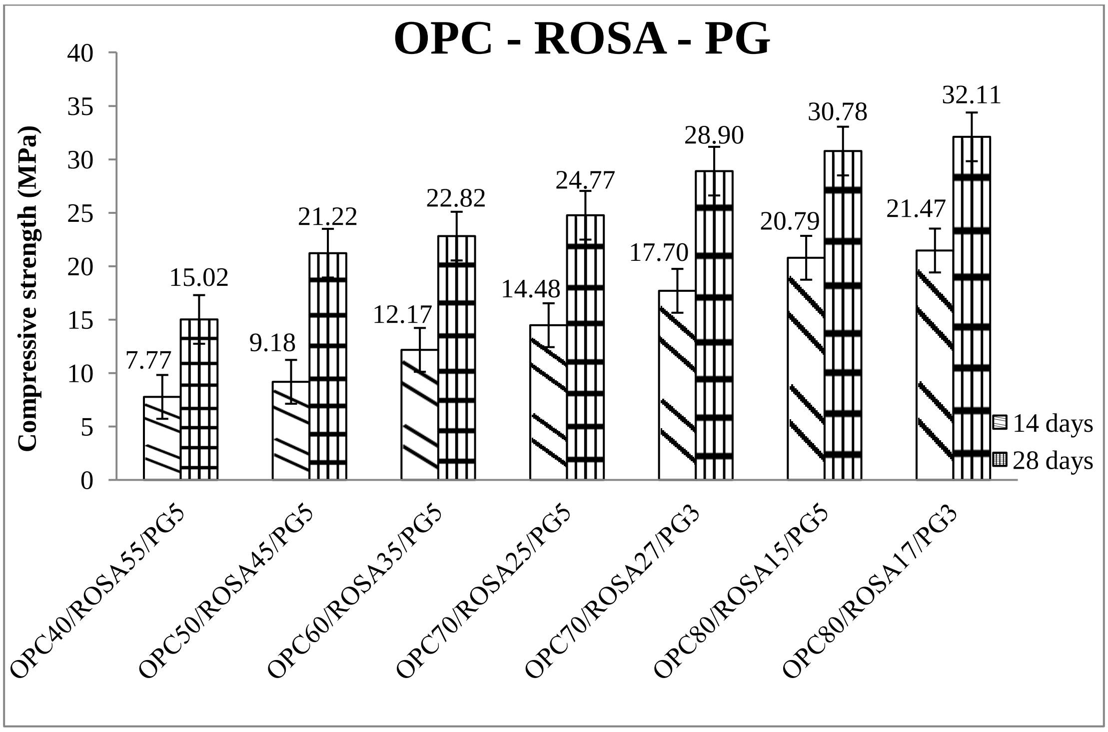


Figure 5.18: Compressive strength of 50x50mm cubes for OPCROSA-PG after 14 & 28 days

Figure 5.19 shows that in OPC-ROSA-PG mixes the effect of increase in OPC content is significant on compressive strength where OPC ranges from 40-80%; whereas increase in ROSA content showed the opposite trend and as the percent of ROSA increased more than 17% the strength decreased.

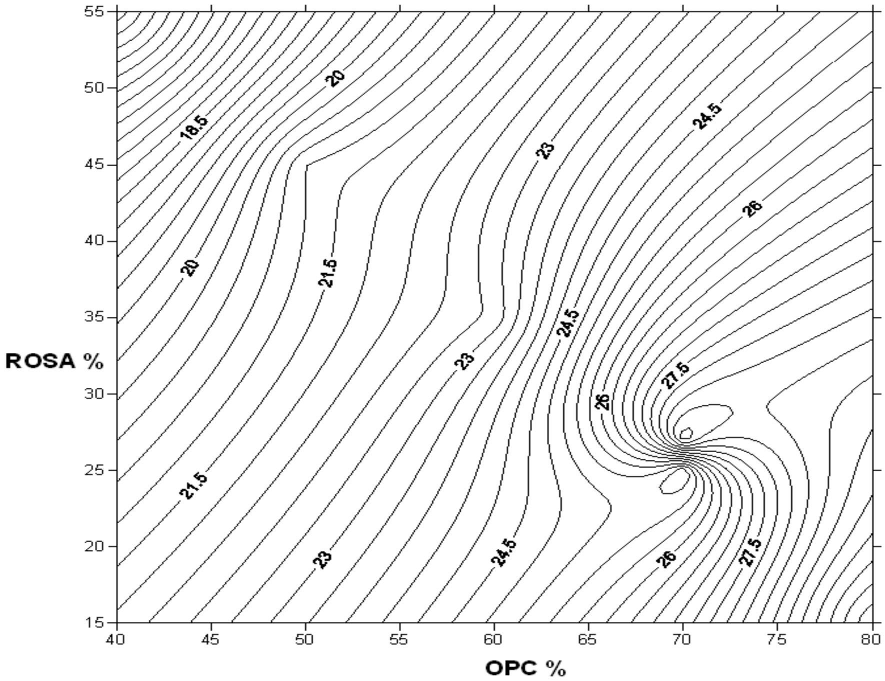


Figure 5.19: Compressive strength contours of 50x50mm cubes for OPC-ROSA-PG after 28 days

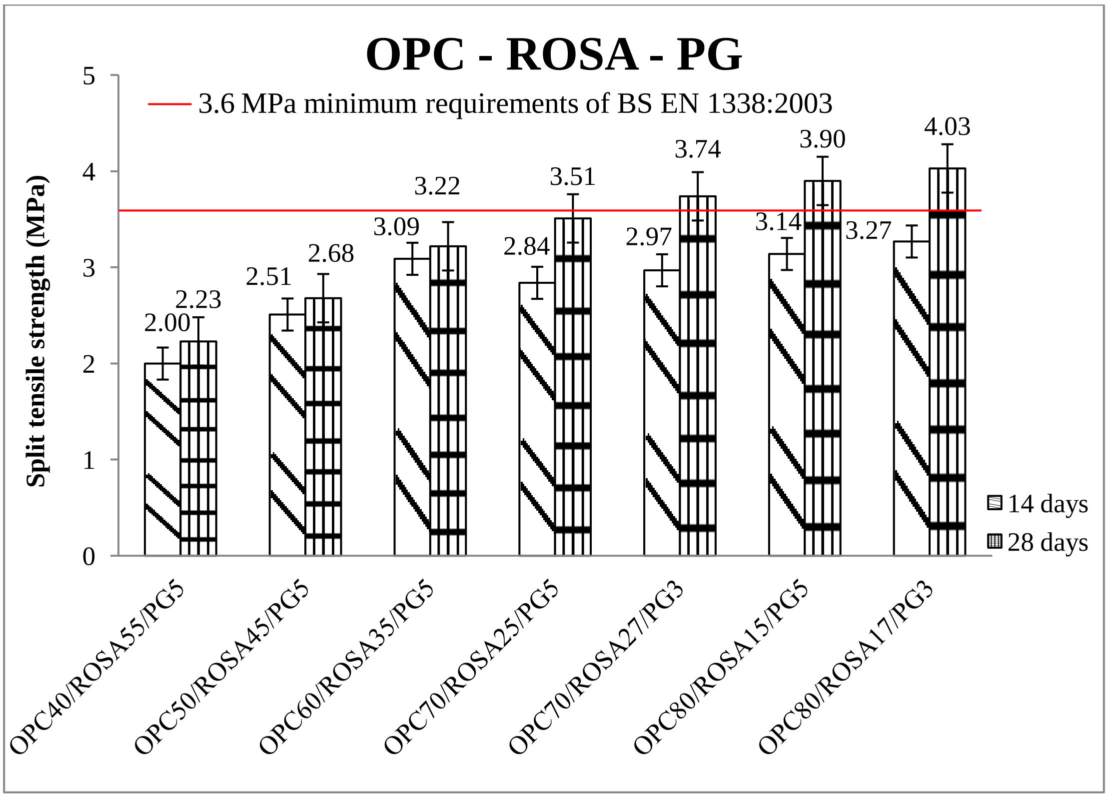


Figure 5.20: Split tensile strength of paving blocks for OPC-ROSA-PG after 14 & 28 days

Figure 5.21 shows that in OPC-ROSA-PG mixes the effect of increase in OPC is considerable on split tensile strength; while increase in ROSA content showed the opposite trend and as the percent of ROSA increased more than 17% the strength decreased. The average ratio of compressive strength to split tensile strength in this group was 7.5.

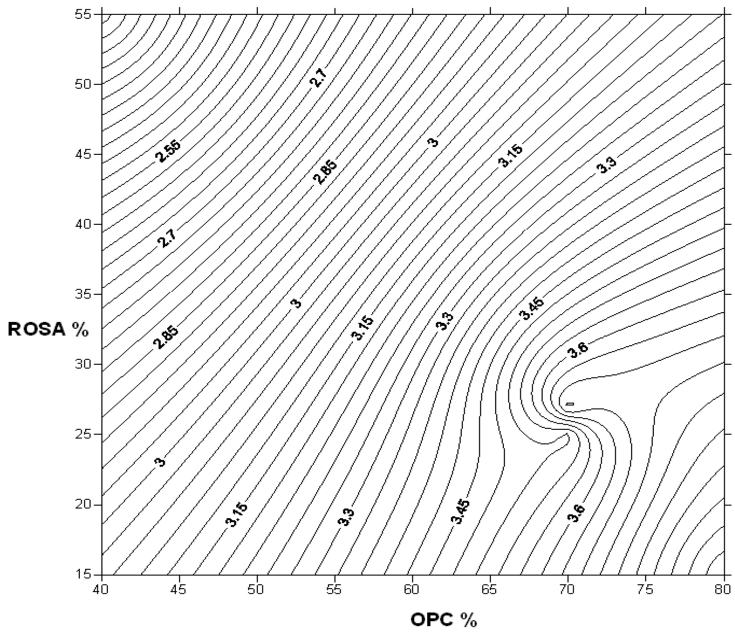


Figure 5.21: Split tensile strength contours of paving blocks for OPC-ROSA-PG after 28 days

5.4.2.6 Binary mixture of OPC-BOS

The results of compressive strength and split tensile strength mixes combing binary components OPC and BOS with W/B ratio 0.15 are shown in figures 5.22 to 5.25. The results of mix containing 60 % ordinary Portland cement (OPC), 40% basic oxygen slag (BOS) showed the highest strength at 14 and 28 days with 55.68MPa in compressive strength and 5.32MPa in split tensile strength. On the other hand, mix containing OPC30-BOS70 presented the lowest strength at 28 days comparing with other mixes in the same group, furthermore all the mixes in the same group was higher than the minimum requirements of the British standard BS EN 1338:2003 at 28 days and confirmed 70% of cement reduction. Figure 5.23 shows that increase in OPC above 40% did not have significant effect on split tensile strength. The average ratio of compressive strength to split tensile strength in this group was 9.6.

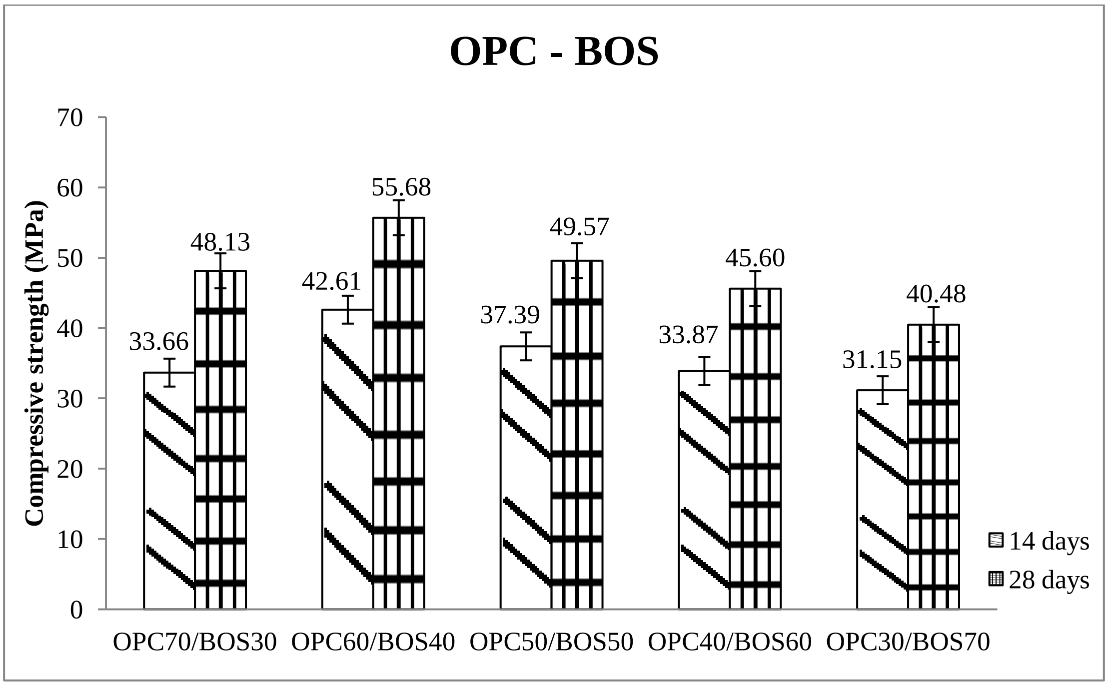


Figure 5.22: Compressive strength of 50x50mm cubes for OPC-BOS after 14 & 28 days

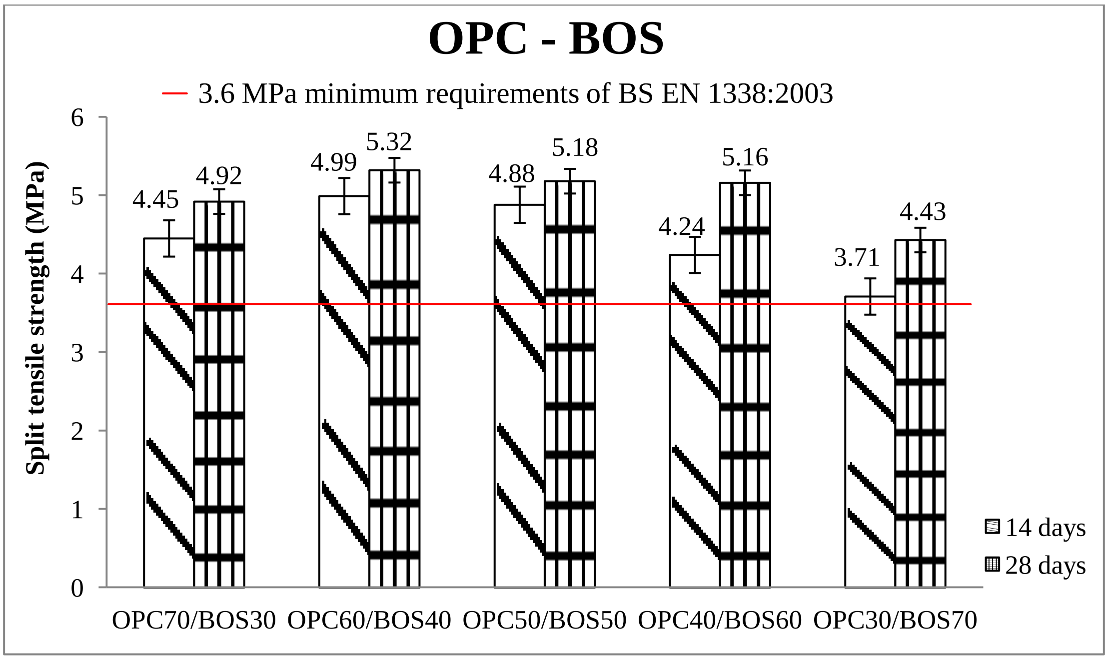


Figure 5.23: Split tensile strength of paving blocks for OPC-BOS after 14 & 28 days

5.4.2.7 Ternary mixture of OPC-GGBS-PG

The results of compressive strength and split tensile strength mixes combing ternary components OPC, GGBS and PG with W/B ratio 0.15 are shown in figures 5.24 to 5.27.

The results of ternary mix containing 70 % ordinary Portland cement (OPC), 25% ground granulated blast furnance slag (GGBS) and 5% plasterboard gypsum (PG) showed the highest compressive strength and tensile strength at 28 days 30.72 MPa and 4.49 MPa, respectively. Moreover, the ternary mix containing OPC60-GGBS35-PG5 also the split tensile strength was higher than 3.6 MPa according to the minimum requirements of the British standard BS EN 1338:2003 after 28 days and this mix can achieved 40% cement replacement.

On the other hand, ternary mix containing OPC40-GGBS15-PG45 showed the lowest strength at 14 and 28 days comparing with other mixes in the same group and did not meet the minimum requirements of the British standard BS EN 1338:2003. Furthermore, as expected the compressive strength of the cube specimens in this group showed the same trend as the paving block specimens.

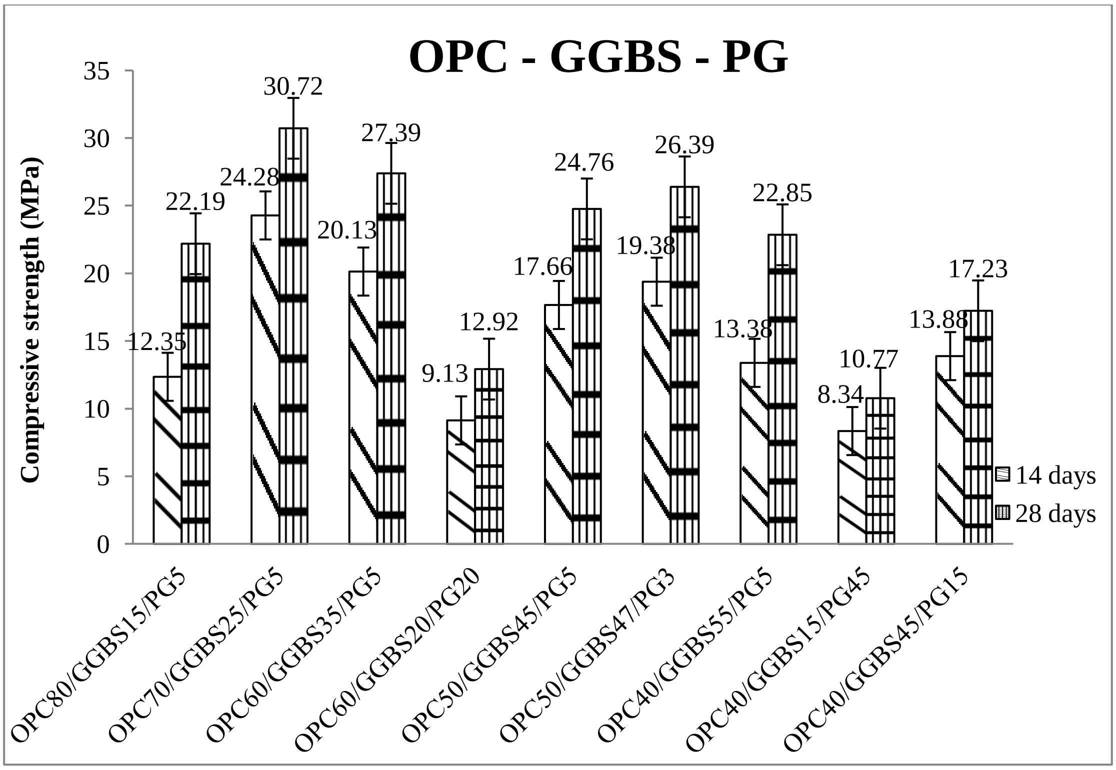


Figure 5.24: Compressive strength of 50x50 mm cubes for OPC-GGBS-PG after 14 & 28 days

Figure 5.25 shows that in OPC-GGBS-PG mixes the effect of increase in OPC content is insignificant on compressive strength where OPC ranges from 40-60%; however GGBS showed beneficial effect in ranges from 15% to 55%. On the other hand, this trend appears to be opposite in mixes where OPC ranges from 60% to 75%.

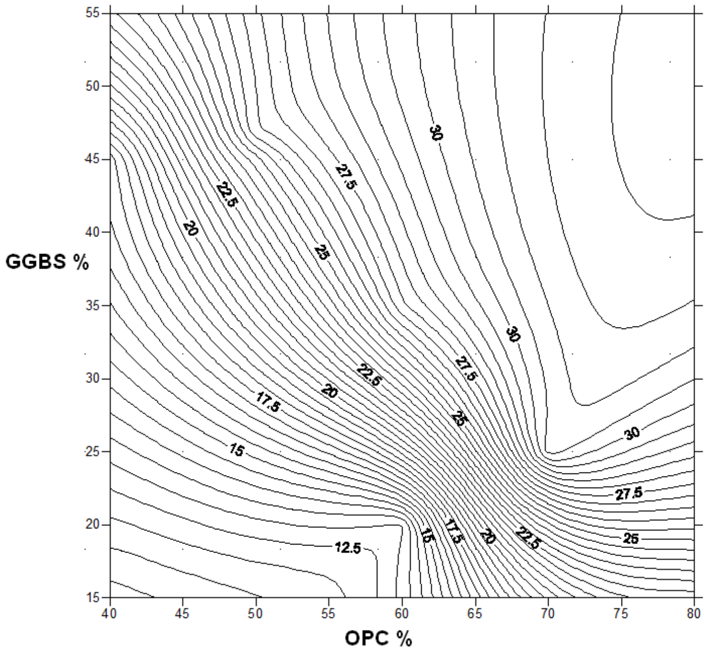


Figure 5.25: Compressive strength contours of 50x50mm cubes for OPC-GGBS-PG after 28 days

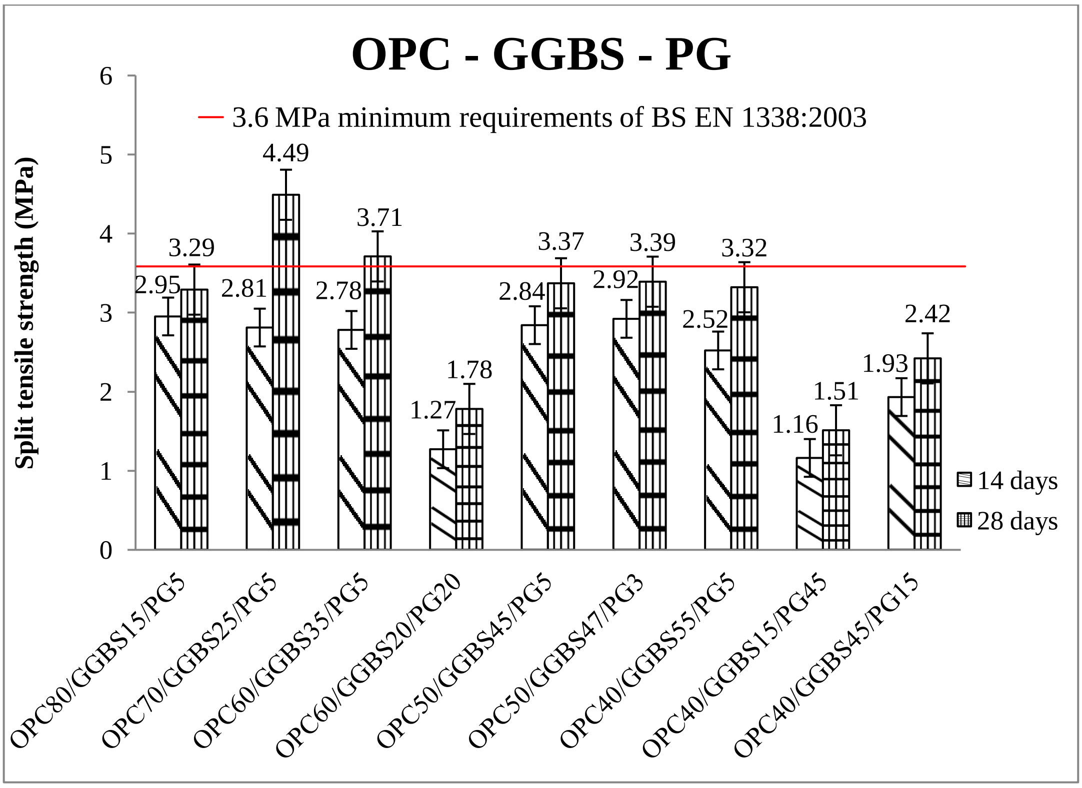


Figure 5.26: Split tensile strength of paving blocks for OPC-GGBS-PG after 14 & 28 days

Figure 5.27 shows that in OPC-GGBS-PG mixes the effect of increase in OPC content is not significant on split tensile strength where OPC ranges from 40% to 60%; whereas GGBS showed beneficial effect in ranges from 15% to 55%. On the other hand, this trend appears to be opposite in mixes where OPC ranges from 60% to 75%. The average ratio of compressive strength to split tensile strength in this group was 7.2.

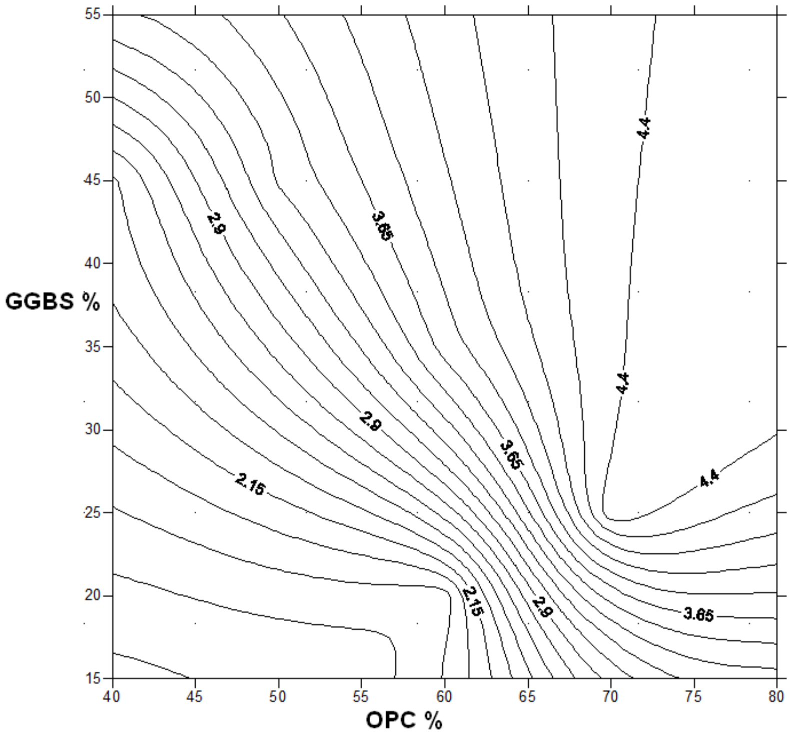


Figure 5.27: Split tensile strength contours of paving blocks for OPC-GGBS-PG after 28 days

5.4.2.8 Ternary mixture of OPC-ROSA-BPD

The results of compressive strength and split tensile strength mixes combining ternary components OPC, ROSA and BPD with W/B ratio 0.15 are shown in figures 5.28 to 5.31. The ternary mix containing 50 % ordinary Portland cement (OPC), 40% run-of-station ash (ROSA) and 10% by-pass dust (BPD) showed the highest compressive strengths 51.36MPa and 4.38MPa in split tensile strength, and the result was higher than 3.6 MPa in split tensile strength as required by the British standard BS EN1338:

2003. Furthermore, the mixes containing OPC40-ROSA40-BPD20 and OPC40-ROSA35-BPD25 were also higher than the minimum requirements of split tensile strength and confirmed that it possible to reduce the percent of cement by 60%. In addition, the paving blocks prepared with ternary mixtures of OPC-ROSA-BPD confirmed the possibility of using up to 25% BPD and 35% ROSA as a replacement for cement and the results are still higher than the minimum requirements after 28 days. Alternatively, increasing the content of by-pass dust (BPD) by more than 25% in ternary combinations of OPC-ROSA-BPD resulted in a lower compressive strength and split tensile strength. This is due to an increase in the alkaline content of the paste resulting from BPD.

On the other hand, ternary mix of OPC30-ROSA40-BPD30 showed the lowest strength at 14 and 28 days comparing with other mixes in the same group. The strength obtained was lower than 3.6 MPa minimum required strength according British standard BS EN 1338:2003 after 28 days.

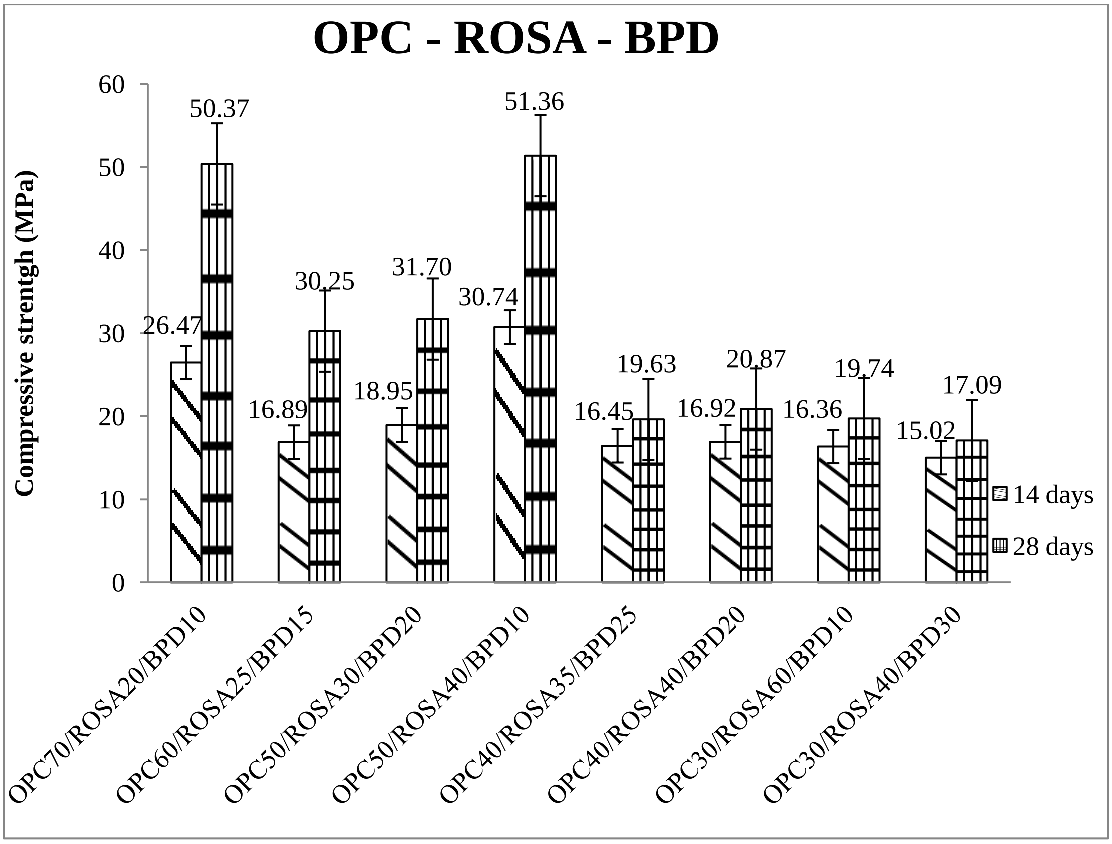


Figure 5.28: Compressive strength of 50x50mm cubes for OPC-ROSA-BPD after 14 & 28 days

Figure 5.29 shows that in OPC-ROSA-BPD mixes the effect of increase in OPC content is significant on compressive strength where OPC ranges from 30-70%; also increase in ROSA content showed the same trend in range 20-45%.

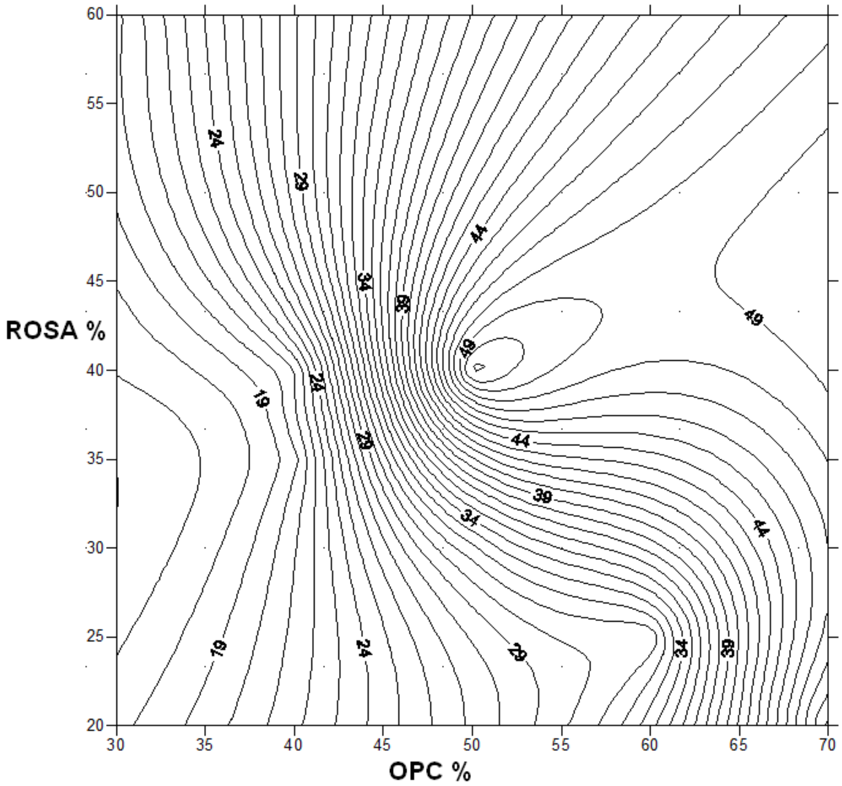


Figure 5.29: Compressive strength contours of 50x50mm cubes for OPC-ROSA-BPD after 28 days

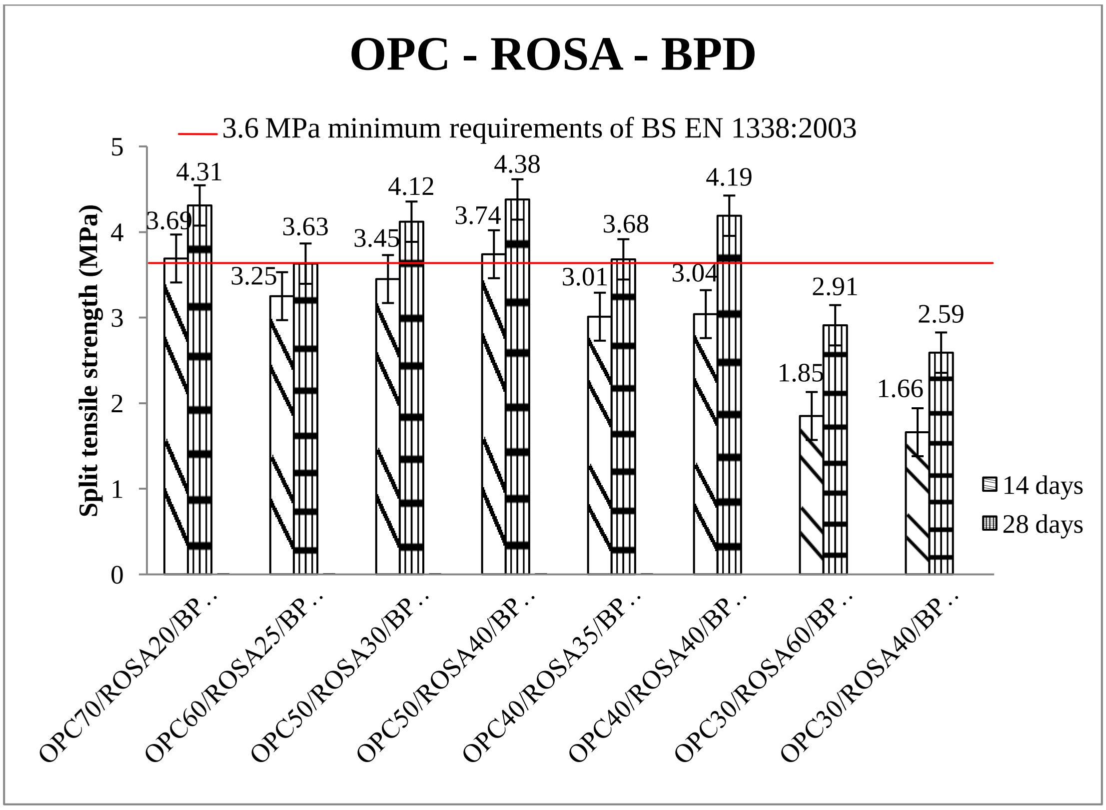


Figure 5.30: Split tensile strength of paving blocks for OPC-ROSA-BPD after 14 & 28 days

Figure 5.31 shows that in OPC-ROSA-BPD mixes the effect of increase in OPC content is significant on split tensile strength where OPC ranges from 30-50%; whereas in range 50-60% the effect is insignificant. On the other hand, the effect of increase in ROSA content is considerable where ROSA ranges from 20% to 45%. The average ratio of compressive strength to split tensile strength in this group was 7.8.

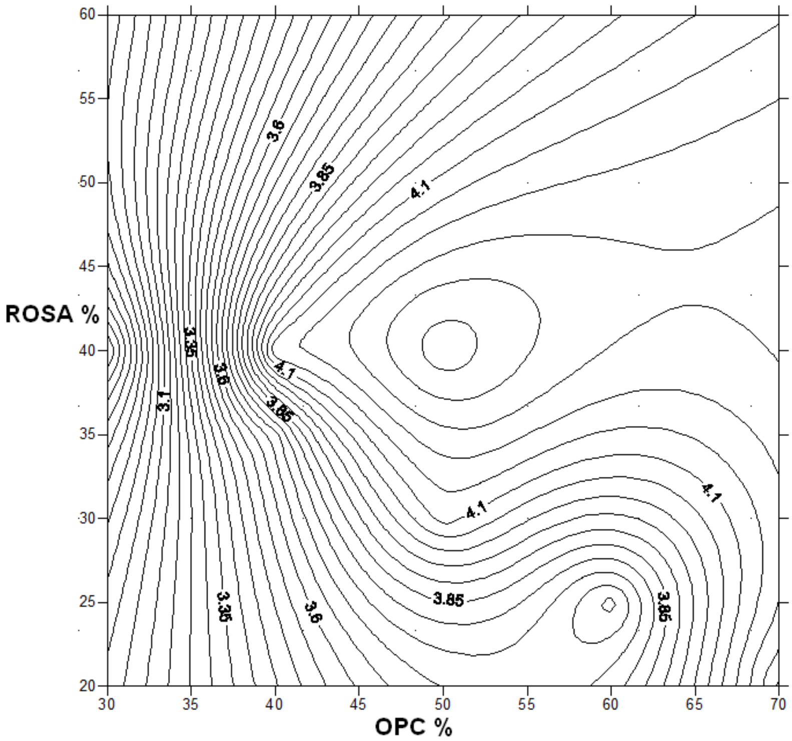


Figure 5.31: Split tensile strength contours of paving blocks for OPC-ROSA-BPD after 28 days

5.4.2.9 Ternary mixture of OPC-GGBS-BPD

The results of compressive strength and split tensile strength of ternary mixes containing OPC, GGBS and BPD with W/B ratio 0.15 are shown in figures 5.32 to 5.35.

The highest compressive strength and split tensile was 48.76MPa and 5.87MPa respectively. These results can be achieved by using 75% ordinary Portland cement (OPC), 20% ground granulated blast furnace slag (GGBS) and 5% by-pass dust (BPD). Another ternary mix was obtained by combining 45% GGBS, 5% BPD and 50% OPC, the split tensile strength results for this mix were higher than the required 3.6MPa by the British standard BS EN1338: 2003. Furthermore, the mix containing OPC40-GGBS55-BPD5 was also higher than the minimum requirements of split tensile strength and confirmed it possible to reduce the percent of cement by 60%. The paving blocks prepared with ternary mixtures of OPC-GGBS-BPD confirm the possibility of using up to 5% BPD and 55% GGBS as a replacement for cement and the results are still higher than the minimum requirements after 28 days.

As it is well established, the ground granulated blast furnace slag (GGBS) is a pozzolanic material which can be used as a cementitious ingredient in either cement or concrete composites. The hydration mechanism of a combination of GGBS and Portland cement is slightly more complex than that of a Portland cement. This reaction involves the activation of the GGBS by alkalis and sulphate to form its own hydration products. Some of these combine with Portland cement products to form further hydrates which have a pore blocking effect. The result is a hardened cement paste that consists of a high concentration of tiny gel pores and a low concentration of large capillary pores, with the same total pore volume. Generally, the rate of strength development is slower than for a Portland cement mortar (Mortar Industry Association, 2008). In this mix, BPD also acts as an alkaline to improve the GGBS hydration with OPC further.

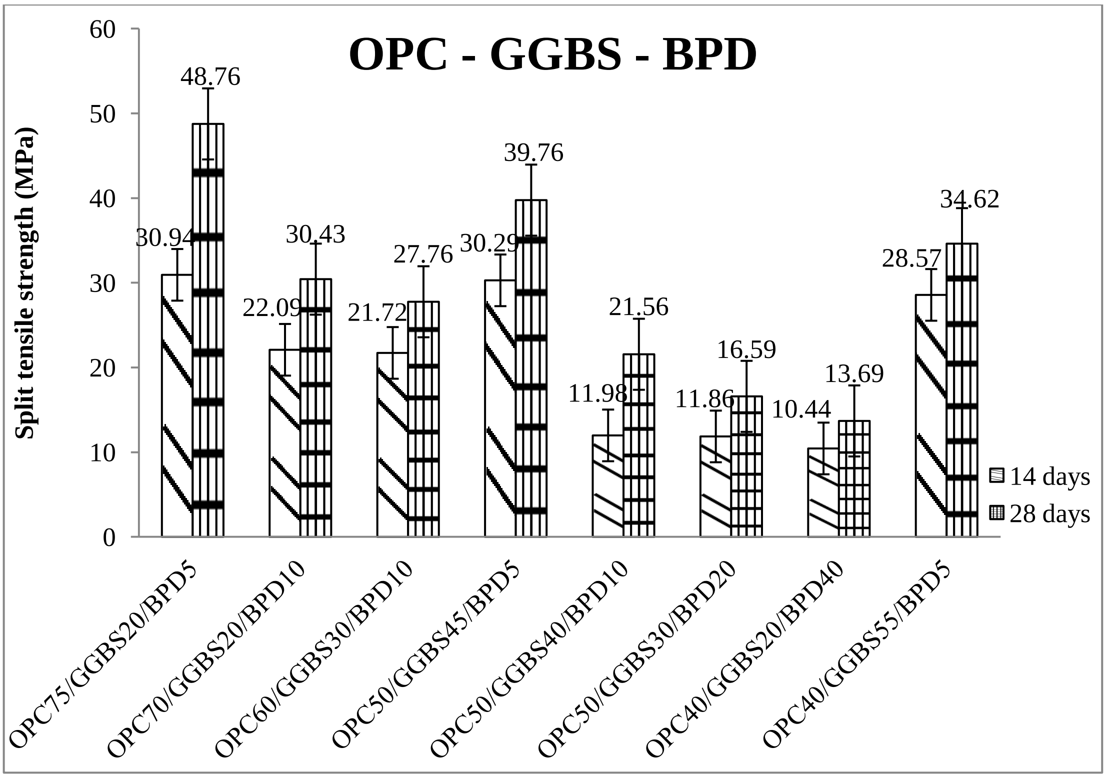


Figure 5.32: Compressive strength of 50x50mm cubes for OPC-GGBS-BPD after 14 & 28 days

Figure 5.33 shows that in OPC-GGBS-BPD mixes the effect of increase in OPC content is considerable on compressive strength where OPC ranges from 50-75%; while increase in GGBS content showed the same trend within the range 35-55%.

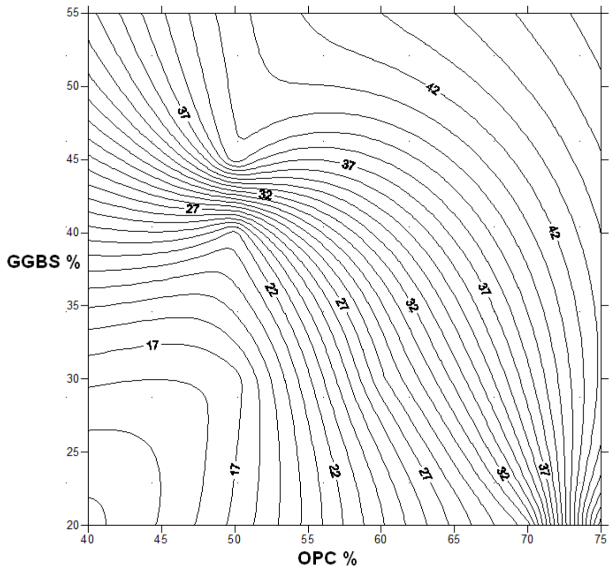


Figure 5.33: Compressive strength contours of 50x50mm cubes for OPC-GGBS-BPD after 28 days

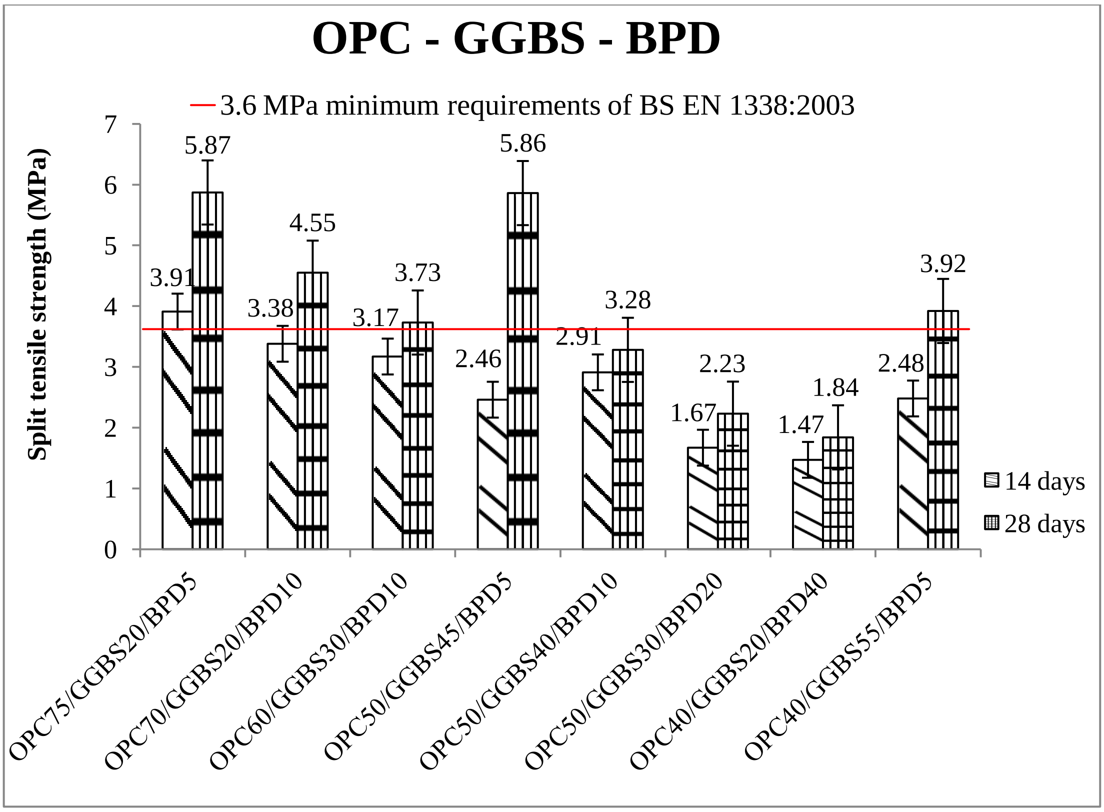


Figure 5.34: Split tensile strength of paving blocks for OPC-GGBS-BPD after 14 & 28 days

Figure 5.35 shows that in OPC-GGBS-BPD mixes the effect of increase in OPC content is significant on split tensile strength where OPC ranges from 50-75%; whereas increase in GGBS content showed the same trend within the range 35-55%. The average ratio of compressive strength to split tensile strength in this group was 7.4.

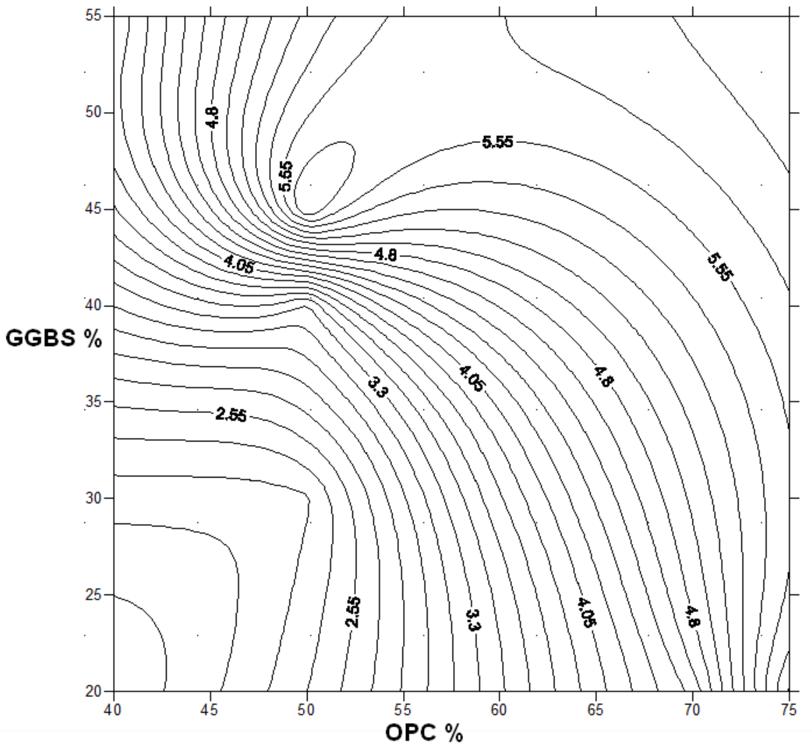


Figure 5.35: Split tensile strength contours of paving blocks for OPC-GGBS-BPD after 28 days

5.4.2.10 Ternary mixture of OPC-BOS-BPD

The results of compressive strength and split tensile strength mixes combining ternary components OPC, BOS and BPD with W/B ratio 0.15 are shown in figures 5.36 to 5.39. The ternary mix containing 40 % ordinary Portland cement (OPC), 55% basic oxygen slag (BOS) and 5% by-pass dust (BPD) showed the highest compressive strengths 47.43MPa and split tensile strength 5.16MPa. Split tensile strength of was higher than 3.6 MPa split tensile strength which is required by the British standard BS EN1338: 2003 confirming that 60% cement reduction can be achieved. The results of mechanical propertied of paving blocks prepared with ternary mixtures of OPC-BOS-BPD confirm the possibility of using up to 10% BPD to satisfy the minimum standard requirements after 28 days.

Alternatively, increasing the by-pass dust (BPD) content by more than 10% in ternary combinations of OPC-BOAS-BPD resulted in a lower compressive strength and split tensile strength. This is due to an increase in the alkaline content of the paste resulting from BPD. On the other hand, ternary mix of OPC40-BOS10-BPD50 showed the lowest strength at 14 and 28 days comparing with other mixes in the same group. The split tensile strength of the mix was lower than 3.6 MPa according to the minimum requirements of the British standard BS EN 1338:2003 at 28 days.

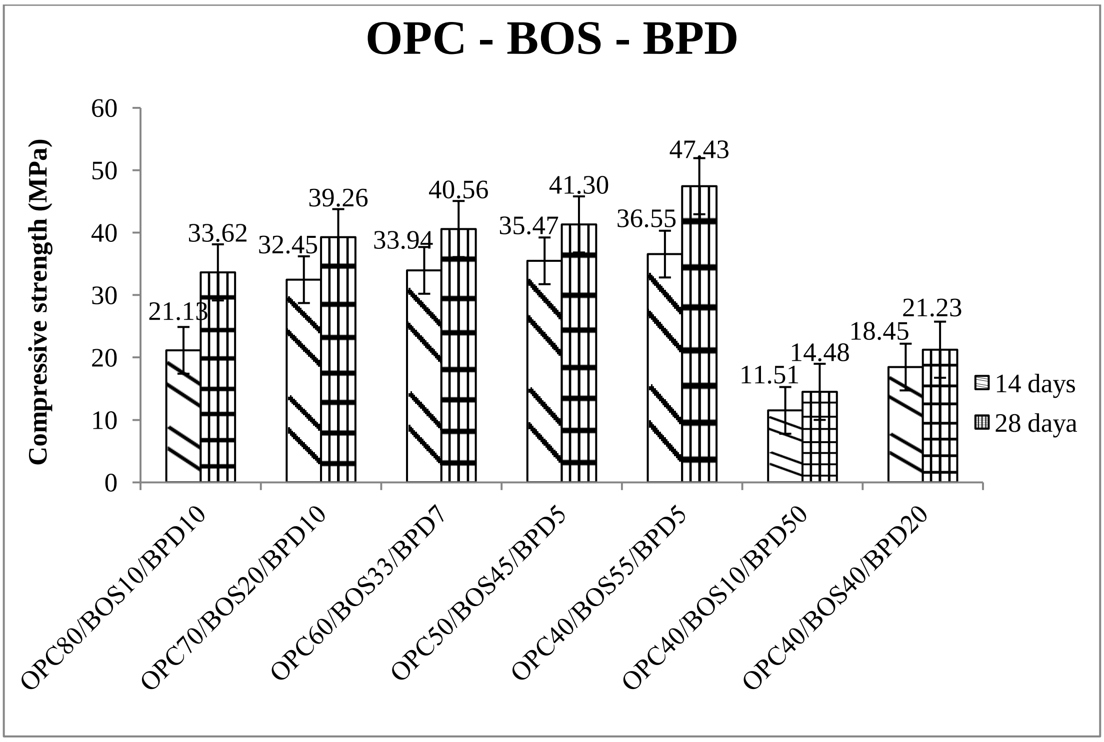


Figure 5.36: Compressive strength of 50x50mm cubes for OPC-BOS-BPD after 14 & 28 days

Figure 5.37 shows that in OPC-BOS-BPD mixes the effect of increase in OPC content is considerable on compressive strength where OPC ranges from 40-80%; whereas increase in BOS content showed the same trend within the range 40-55%, as the percentage of BOS increased the strength increased.

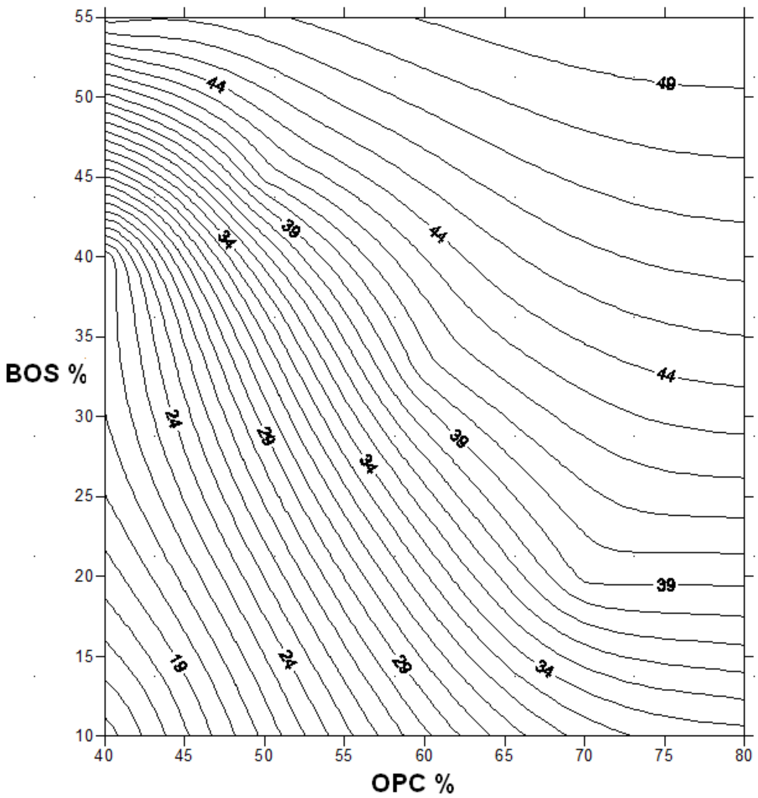


Figure 5.37: Compressive strength contours of 50x50mm cubes for OPC-BOS-BPD after 28 days

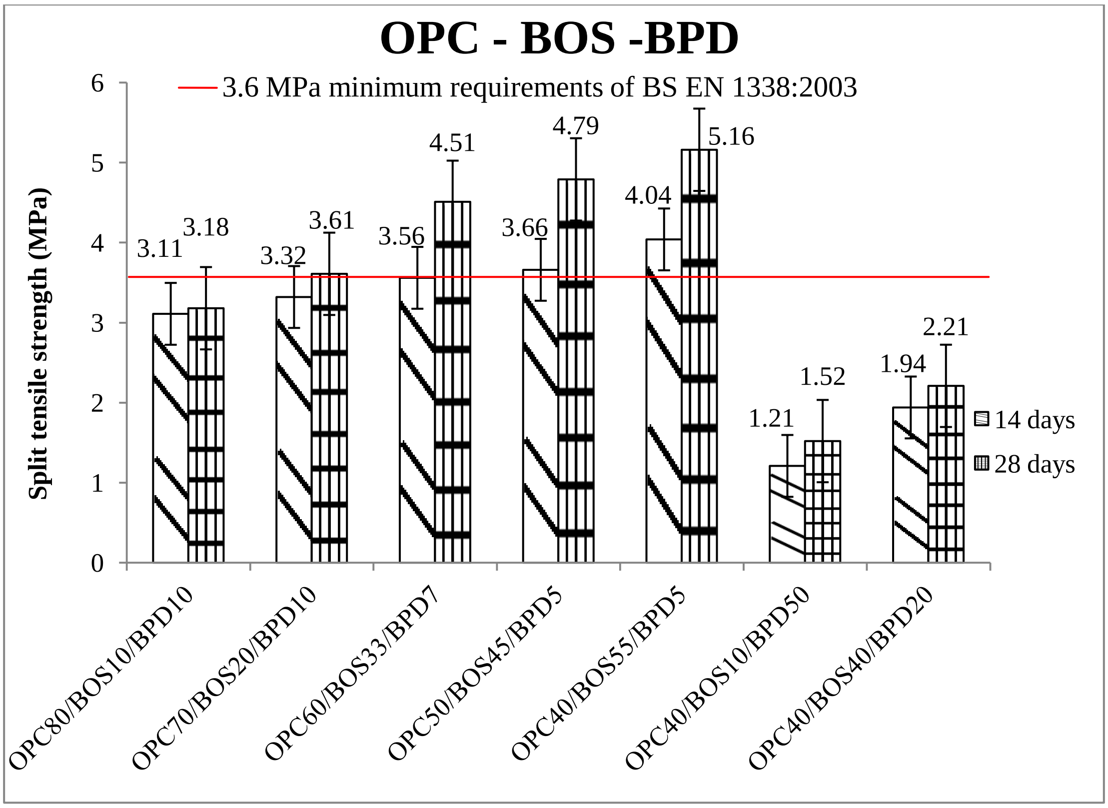


Figure 5.38: Split tensile strength of paving blocks for OPC-BOS-BPD after 14 & 28 days

Figure 5.39 shows that in OPC-BOS-BPD mixes the effect of increase in OPC content is significant on split tensile strength where OPC ranges from 40-80%; while increase in BOS content showed the same trend within the range 40-55%, as the percent of BOS increased the strength increased. The average ratio of compressive strength to split tensile strength in this group was 9.6.

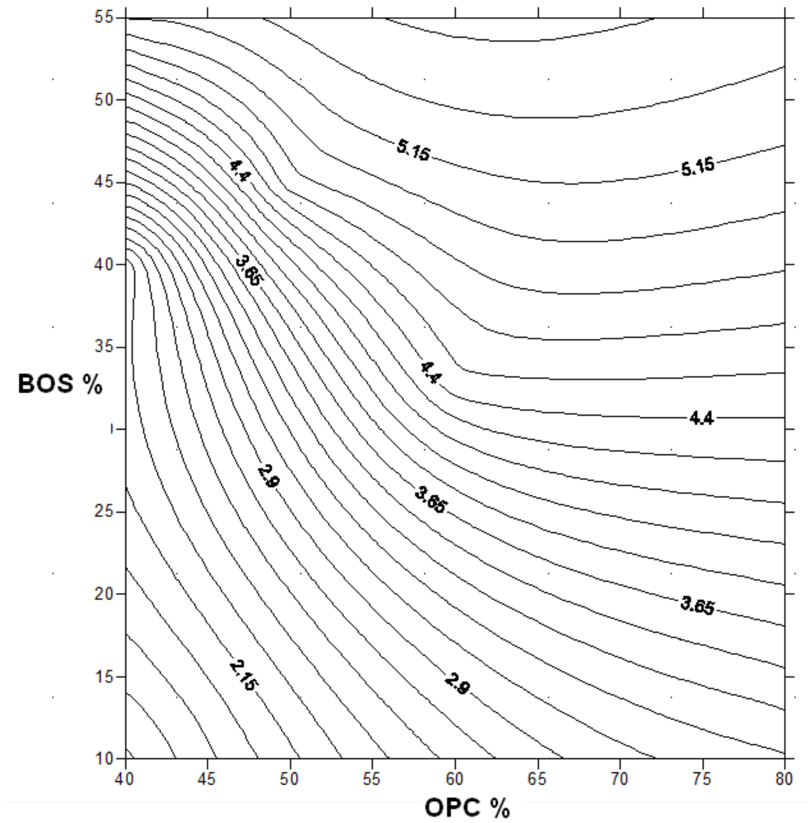


Figure 5.39: Split tensile strength contours of paving blocks for OPC-BOS-BPD after 28 days

5.4.3 Summary of optimum mixes from phase1:

A summary of the results of the sampled mixes in the first phase that pass the minimum requirements for split tensile strength, in accordance to BS EN1338 (British Standard Institute, 2003), after 28 days is shown in table 5.7. All results were inputted in Minitab 16 Software and the optimum mixes were selected to be used in the second phase.

The discussion section indicates that the ratio of compressive strength to split tensile strength results for all mixes in the first phase varied between 5.5 and 9.6. Mixes with higher compressive strength produced a higher ratio. It was found that as compressive strength increases, the ratio also increase as detailed in Table 10.94 in the appendix.

Results indicated that the compressive to split tensile strength ratio for mixes with compressive strength above 40 MPa is almost similar to those reported for ordinary concrete using 100mm cube and 100mm diameter cylinder. Also, no direct comparison for different ratios was found in different literatures for 50mm concrete cubes and paving blocks.

Table 5.7: The summary of the mixes results which satisfy the minimum requirements on split tensile strength according to BS EN1338 (British Standard Institute, 2003)

Mix code	Split tensile strength at 28 days (MPa)	Mix code	Split tensile strength at 28 days (MPa)
OPC70/ROSA30	4.25	OPC70/ROSA27/PG3	3.74
OPC60/ROSA40	5.22	OPC80/ROSA15/PG5	3.90
OPC50/ROSA50	5.42	OPC80/ROSA17/PG3	4.03
OPC40/ROSA60	3.72	OPC70/BOS30	4.92
OPC40/GGBS30/BOS30	4.30	OPC60/BOS40	5.32
OPC30/GGBS40/BOS30	4.45	OPC50/BOS50	5.18
OPC30/GGBS30/BOS40	5.39	OPC40/BOS60	5.16
OPC30/GGBS35/BOS35	4.38	OPC30/BOS70	4.43
OPC20/GGBS40/BOS40	4.09	OPC70/GGBS25/PG5	4.49
OPC20/GGBS30/BOS50	5.41	OPC60/GGBS35/PG5	3.71
OPC70/BOS25/PG5	4.44	OPC70/ROSA20/BPD10	4.31
OPC60/BOS35/PG5	5.09	OPC60/ROSA25/BPD15	3.63
OPC50/BOS45/PG5	4.89	OPC50/ROSA30/BPD20	4.12
OPC50/BOS47/PG3	4.77	OPC50/ROSA40/BPD10	4.38
OPC40/BOS55/PG5	4.57	OPC40/ROSA35/BPD25	3.68
OPC30/BOS65/PG5	4.04	OPC40/ROSA40/BPD20	4.19
OPC30/ROSA35/BOS35	4.13	OPC75/GGBS20/BPD5	5.87
OPC40/ROSA30/BOS30	4.60	OPC70/GGBS20/BPD10	4.55
OPC50/ROSA25/BOS25	4.79	OPC60/GGBS30/BPD10	3.73
OPC50/ROSA20/BOS30	4.65	OPC50/GGBS45/BPD5	5.86
OPC52/ROSA30/BOS18	5.14	OPC60/BOS33/BPD7	4.51
OPC60/ROSA20/BOS20	4.94	OPC50/BOS45/BPD5	4.79
OPC70/ROSA15/BOS15	4.67	OPC40/BOS55/BPD5	5.16

6. Data Analysis

6.1 Response Surface Method (RSM)

6.1.1 Introduction

It is not possible to test all the different combinations of raw materials; this is because it is very time consuming, there is a shortage of materials, lack of space is also another reason. In order to gain a better insight into physical properties of unmade pastes, such as split tensile strength and compressive strength, prediction models will be used in this chapter.

During recent decades there has been lots of focus on the discovery of efficient statistical methods that can be used for consistent analysis of experimental results. The recent approach used for solving complex problems is the Response Surface Method (RSM) technique. The Response Surface Method (RSM) is considered to be one of the most widely used methods in data analysis. RSM provides important applications in the design, development and formulation of new products, as well as in the improvement of existing product designs (Montgomery 2005). In this study RSM is used to predict the 28 day split tensile strength and compressive strength of ternary combinations of the raw materials. This method was found to be the most appropriate methods for analysing the data of this research.

6.1.2 Triangular Coordinate Systems

The triangular coordinate system let one to visualize the relationship between the components in a three-component mixture. As most of the mixes made were ternary mixes, this system was thought to be best way to show the relationships found and is presented in this chapter.

In a mixture, components are restricted by one another, in that the components must add up to the total amount present in the system. Furthermore, triangular coordinate systems in this section show the minimum values of the x1, x2, and x3 components as 0, with the maximum value being at 1. The following illustration (Fig. 6.1) shows the general layout of a triangular coordinate system. The components in the mixture models are referred to in terms of their proportion to the whole system, with the total value adding up to 1. The vertices of the triangle represent pure mixtures or single-component blends. In pure mixtures, the proportion of one component is 1 and the rest are 0. Any point present along the edges of the triangle represents blends that have one component absent. The illustration in figure 6.1 shows the location of different blends.

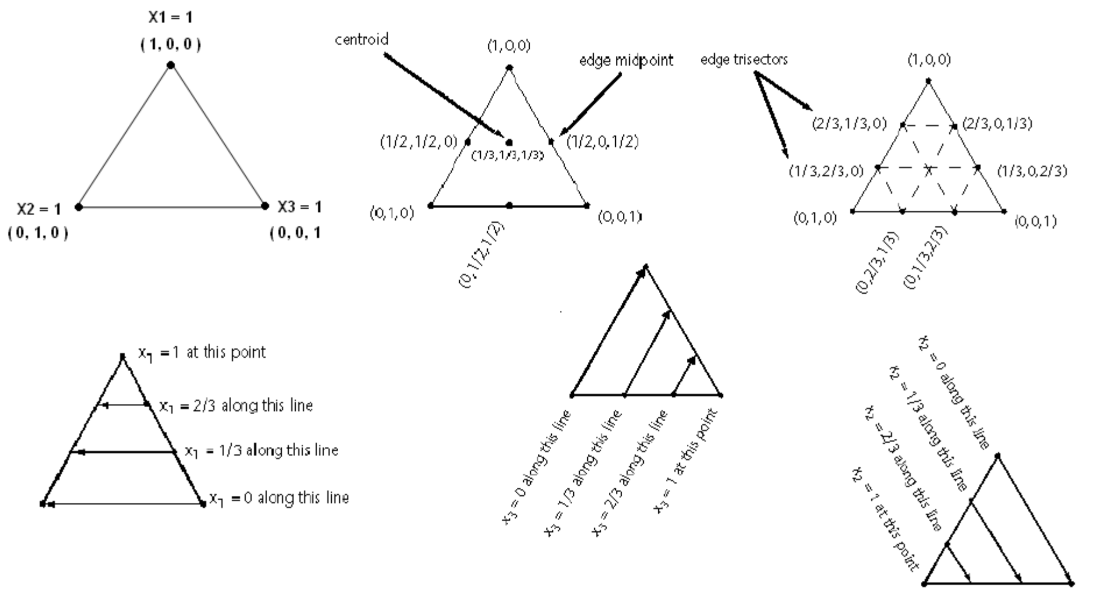


Figure 6.1: Simple illustration showing coordinate systems at edge tri-sector, vertices and centroid

Each location on the triangles in the above illustrations represents a different blend incorporated into the mixture.

For example:

• The midpoints that are near the edge two-blend mixtures in which one component makes up 1/2 and a second component makes up ½ of the mixture.

• The tri-sectors near the edge are also two-blend mixtures in which one component makes up 1/3 and another component makes up 2/3 of the mixture. These points divide the triangle edge into 3 equal parts.

• Finally, the centre point (or centroid) is the complete mixture in which all components are present in equal proportions (1/3, 1/3, 1/3). Complete mixtures are on the interior of the design space and are mixtures in which all of the components are simultaneously present (Simon et al, 1997).

6.1.3 Mixture design

According to Montgomery (2005), in mixture experiments, the factors are the components or ingredients of a mixture, and consequently, their levels are not independent. For instance, if $x_1, x_2, ..., x_p$ denote the proportions of p components of a mixture, then

$$0 \le x_i \le 1 \qquad i = 1, 2, ..., p \qquad \text{Equation 6.1}$$

And

$$x_1 + x_2 + ... + x_p = 1 \qquad \text{(i.e., 100 percent)} \qquad \text{Equation 6.2}$$

For three-component mixtures, the mixture space is a triangle with vertices corresponding to formulations that are pure blends (mixture that is 100 % of a single component). Mixture models differ from usual polynomials that are employed in response surface work due to the constraint of: $\sum x_i = 1$. The standard forms of the mixture models that are in widespread use are as follows:

Linear:

$$E(y) = \sum_{i=1}^{p} \beta_i x_i \qquad \text{Equation 6.3}$$

Quadratic:

$$E(y) = \sum_{i=1}^{p} \beta_i x_i + \sum\sum_{i<j}^{p} \beta_{ij} x_i x_j \qquad \text{Equation 6.4}$$

In this research, a quadratic polynomial model has been used for the response surface because it can predict more accurate results than a linear model for binary and ternary mixes. The linear model is only valid when there are no interactions between components.

The main aim of this chapter it to use experimental data to predict the 28 day split tensile strength and compressive strength of ternary combinations. A quadratic form was selected to develop the model for different combinations; the different combinations are OPC, ROSA, BOS, GGBS, PG, and BPD. Each mix is a combination of three materials; the design has been done for the following ternary groups as shown in figure 6-2:

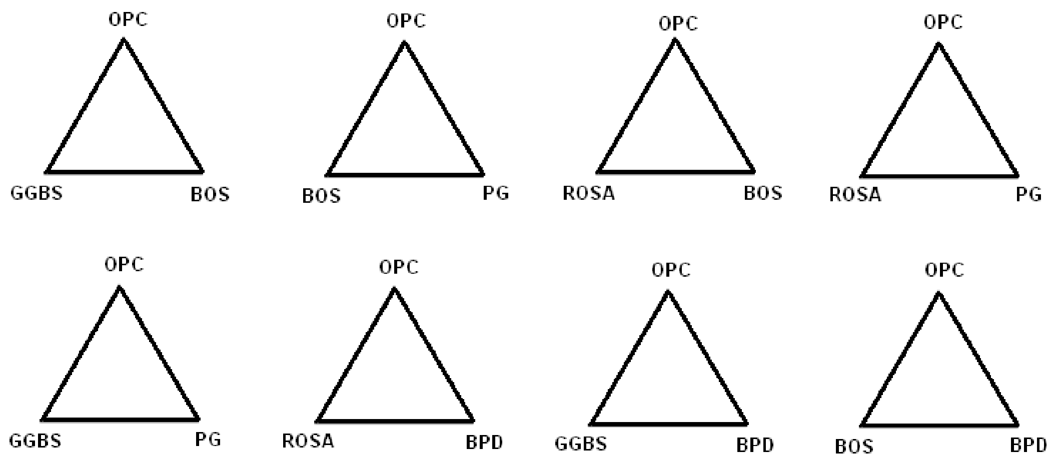


Figure 6.2: Different groups of mixes

MINITAB 16 software was used to analyse all mixes. Split tensile strength and compressive strength of experimental mixes after 28 days were analysed. The results and outputs from the software are presented in this part.

6.1.4 Results of Mixture Design and Regression

Mixture contour plots were drawn using MINITAB 16 software and are presented in this chapter. Prediction models in the form of quadratic equations have been produced for each group and are presented separately for each mix, therefore the results of split tensile strength and compressive strength after 28 days are obtained from the prediction models.

Furthermore, the amount of error has been calculated for all groups.

Error % = ABS (experimental Cs - estimated Cs) / (experimental Cs*100) Equation 6-7

Error % = ABS (experimental Ts - estimated Ts) / (experimental Ts*100) Equation 6-8

Where:

ABS = Absolute value.

TS = Split tensile strength after 28 days (MPa).

CS= Compressive strength after 28 days (MPa).

6.2 Data analysis of binary mixes

6.2.1 OPC-ROSA

6.2.1.1 Compressive strength of mix OPC-ROSA

The mixture design, average compressive strength and predicted compressive strength results for the samples are given in Table 6.1 below. The compressive strength was determined by testing three identical specimens and calculating the average of the three, while predicted compressive strength by using Equation 6.7.

The software MINITAB 16 was used to derive the quadratic model coefficients as follows:

Equation 6.7:

$$\boxed{CS = 0.003 \times OPC - 0.162 \times ROSA + 00.0135 \times OPC \times ROSA}$$

The Equation 6.7 used for OPC and ROSA content ranges from 30 to70%.

It can be seen that the predicted compressive strength results as shown in the same table were very similar to the experimental compressive strength results. The average percentage error was 2.4%; a trend can be seen in the result that as the OPC content is reduced the percentage error decreases. This trend relates to the equation used for this group. The predicted strength for other mix proportions were not examined for the binary mixes because only the limiting percentage by weight range of materials was required for this phase. In the ternary mix designs however all the process of finding the optimum mix design and testing the predicted results were performed.

Table 6.1: Predicted and average compressive strength at 28 days for mix OPC-ROSA

Mix No.	OPC (%)	ROSA (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	70	30	24.2	23.7	2.0
2	60	40	24.9	26.1	4.8
3	50	50	26.4	25.8	2.2
4	40	60	23.2	22.8	1.7
5	30	70	16.8	17.1	1.7

Average percentage error of data = 2.4%

R-squared = 95.82%

6.2.1.2 Split tensile strength of mix OPC-ROSA

The mixture design, average split tensile strength and predicted split tensile strength results are given in Table 6.2 below. The split tensile strength was determined by testing three identical specimens and calculating the average of the three and split tensile strength was predicted by using Equation 6.8.

Quadratic model coefficients were derived using MINITAB 16 software:

Equation 6.8:

$$\boxed{TS = -\ 0.0225714\times OPC - 0.0655714\times ROSA + 0.00378571\times OPC\times ROSA}$$

The Equation 6.8 is applicable for OPC and ROSA content 30-70%.

The average split tensile strength and predicted split tensile strength by using are given in Table 6.2 below by using Equation 6.8. As it can be seen, the predicted split tensile strength results as shown in the Table 6.2 were close to the experimental split tensile strength results. The average percentage error was 6.0% in this group. However, mix 4 had a big percentage error; this is due to the equation trend.

Table 6.2: Predicted and average split tensile strength at 28 days for mix ROSA-OPC

Mix No.	OPC (%)	ROSA (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	70	30	4.3	4.4	2.3
2	60	40	5.2	5.1	1.9
3	50	50	5.4	5.1	5.5
4	40	60	3.7	4.2	13.5
5	30	70	2.9	2.7	6.8

Average percentage error of data = 6.0%.

R-squared = 88.83%.

The surface plot of ROSA, OPC and the experimental split tensile strength after 28 days is shown in Figure 6.3 below. It can be seen that the effect of ROSA content in split tensile strength is significant. The increase in ROSA content up to 50% resulted in the highest strength.

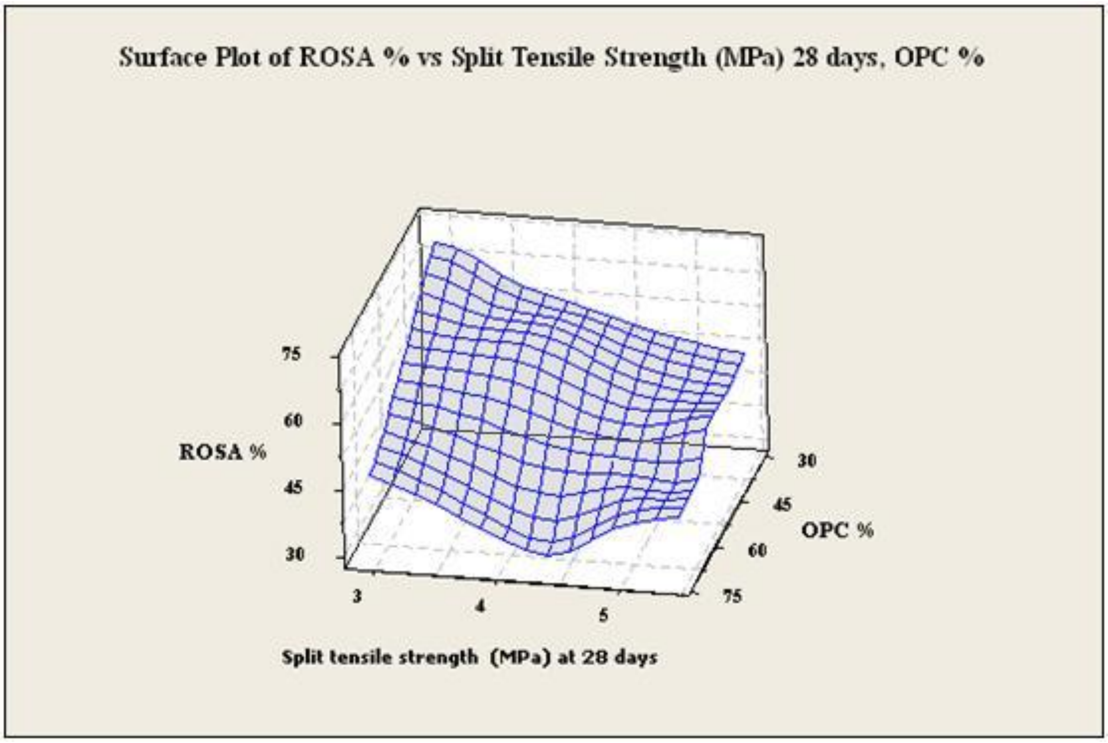


Figure 6.3: Surface plot of ROSA, OPC and split tensile strength after 28 days

6.2.2 OPC-BOS

6.2.2.1 Compressive strength of mix OPC-BOS

The mixture design, average compressive strength and predicted compressive strength results for the samples are given in Table 6.3 below. The results of predicted compressive strength were obtained by using Equation 6.9.

Quadratic model coefficients were derived using MINITAB 16:

Equation 6.9:

$$\boxed{CS = 0.222714 \times OPC - 0.0302857 \times BOS + 0.0166429 \times OPC \times BOS}$$

The Equation 6.9 is valid for OPC and BOS content between 30-70%.

The Table 6.3 shows that the difference between the predicted and experimental results were very small, therefore the average percentage error for this batch was 3.6%. Furthermore, the percentage error trend in this group relates to Equation 6.9, which indicates that as the percentage of OPC is reduced the percentage error decreases. The range of percentage error amongst the group is between 2.2% to 3.4%, this excludes mix 2 which shows higher a percentage in comparison to other mixes from the same group.

Table 6.3: Predicted and average compressive strength at 28 days for mix OPC-BOS

Mix No.	OPC (%)	BOS (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	70	30	48.1	49.6	3.1
2	60	40	55.6	52.0	6.4
3	50	50	49.5	51.2	3.4
4	40	60	45.6	47.0	3.0
5	30	70	40.4	39.5	2.2

Average percentage error of data = 3.6%

R-squared = 83.01%

6.2.2.2 Split tensile strength of mix OPC-BOS

The mixture design, average split tensile strength and predicted split tensile strength results for the samples are given in Table 6.4 below. The predicted split tensile strength results were obtained using Equation 6.10.

Quadratic model coefficients were derived using MINITAB 16 and the equation is as follows:

Equation 6.10:

$$TS = 0.0177143 \times OPC + 0.00671429 \times BOS + 0.00164286 \times OPC \times BOS$$

The Equation 6.10 used for OPC and BOS content between 30-70%.

It can be seen in Table 6-4 that the difference between the predicted and experimental split tensile strength results is insignificant. The average percentage error for the results in this group was 0.7%. Furthermore, the error trend in this group relates to Equation 6.10, which indicates that the maximum error is 1.9%.

Table 6.4: Predicted and average split tensile strength at 28 days for mix OPC-BOS

Mix No.	OPC (%)	BOS (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	70	30	4.9	4.9	0.0
2	60	40	5.3	5.3	0.0
3	50	50	5.2	5.3	1.9
4	40	60	5.2	5.1	1.9
5	30	70	4.4	4.4	0.0

Average percentage error of data = 0.7%

R-squared = 92.38%

The surface plot of BOS, OPC and the experimental split tensile strength results after 28 days is shown in Figure 6.4 below. The effect of BOS content on split tensile strength is insignificant. As shown in the figure below, the optimum BOS content that gave the highest strength was 40%.

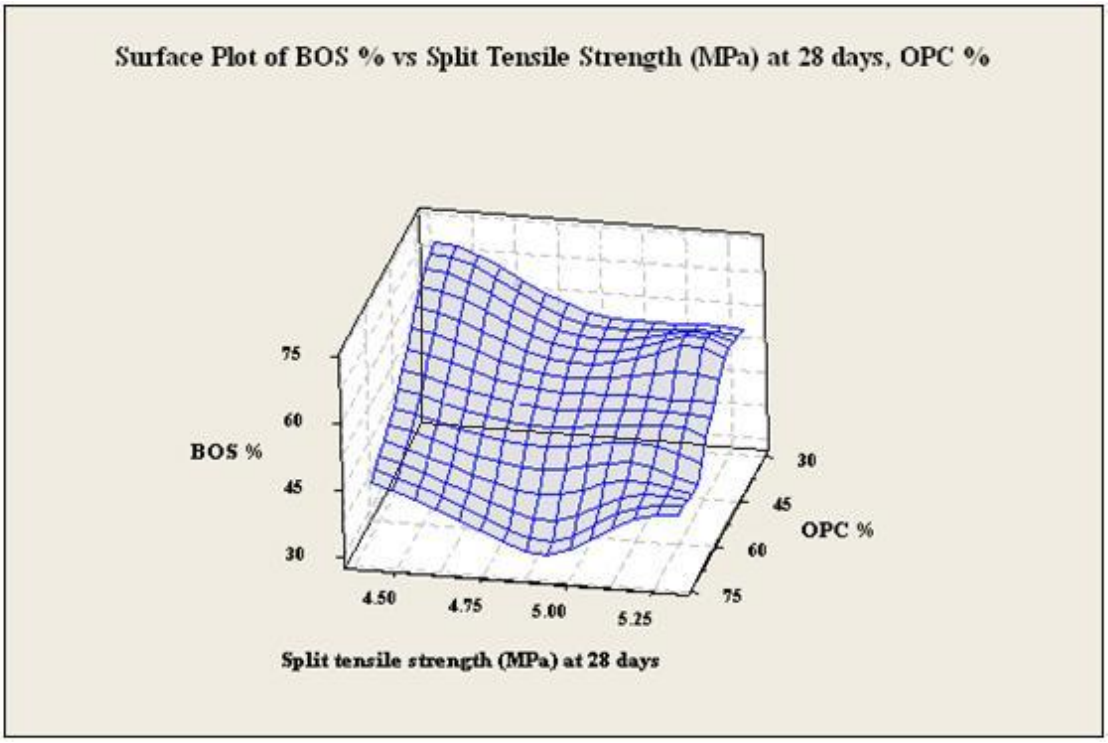


Figure 6.4: Surface plot of BOS, OPC and split tensile strength after 28 days

6.3 Data analysis of ternary mixes

6.3.1 OPC-GGBS-BOS

6.3.1.1 Compressive strength of mix OPC-GGBS-BOS

The mixture design, average compressive strength and predicted compressive strength results for the samples are given in Table 6.5.

Figure 6.5 shows the simplex design plot for the OPC-GGBS-BOS mixtures. The red point inside the triangle represents the mixes made in this group.

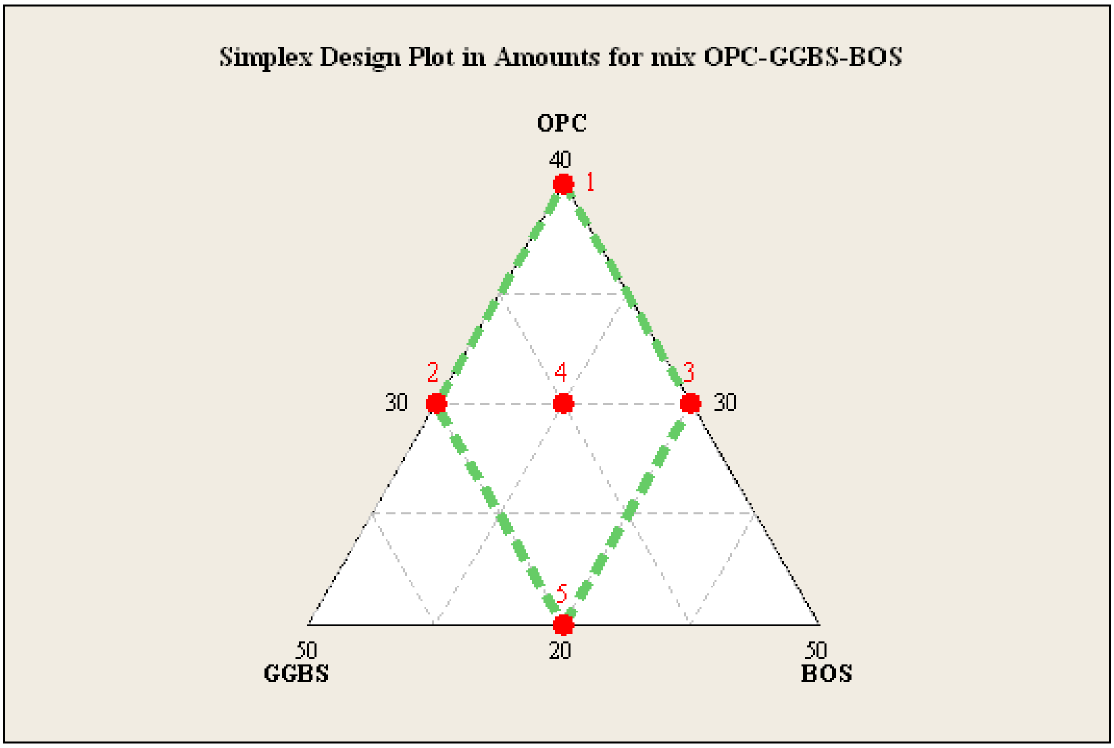


Figure 6.5: Simplex design plot for mixes OPC-GGBS-BOS

The quadratic model coefficients were derived using MINITAB 16:

Equation 6.11:

$$CS = -2.05080 \times OPC - 1.68313 \times GGBS + 1.79487 \times BOS + 0.0849333 \times OPC \times GGBS$$

The Equation 6.11 is applicable for OPC 20-40%, GGBS 30-40% and BOS 30-40%. The predicted compressive strength was obtained using Equation 6.11 as shown in Table 6.5 below. The percentage error between predicted and experimental compressive strength results was insignificant, this excludes mix 4. The range of percentage error was between 0.0% and 8.1%. The overall average percentage error for this group was 3.5%.

Table 6.5: Predicted and average compressive strength for mix OPC-GGBS-BOS

Mix No.	OPC (%)	GGBS (%)	BOS (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	40	30	30	23.2	23.2	0.0
2	30	40	30	25.5	26.9	5.4
3	30	30	40	34.8	36.2	4.0
4	30	35	35	34.4	31.6	8.1
5	20	40	40	31.4	31.4	0.0

Average error of data = 3.5%

R-squared = 89.07%

6.3.1.2 Split tensile strength of mix OPC-GGBS-BOS

The mixture design, average split tensile strength and predicted split tensile strength results are given in Table 6.6 below.

Figure 6.6 shows the mixture contour plot of split tensile strength for the OPC-GGBS-BOS specimen. The figure indicates that the optimum percentage of each component to give the highest tensile strength is 20% OPC, 30% GGBS and 50% BOS as this is the darker colour in the triangular in Figure 6.6. The experimental result confirmed this and showed that 20% OPC, 30% GGBS and 50% BOS gave a split tensile strength 5.4 MPa.

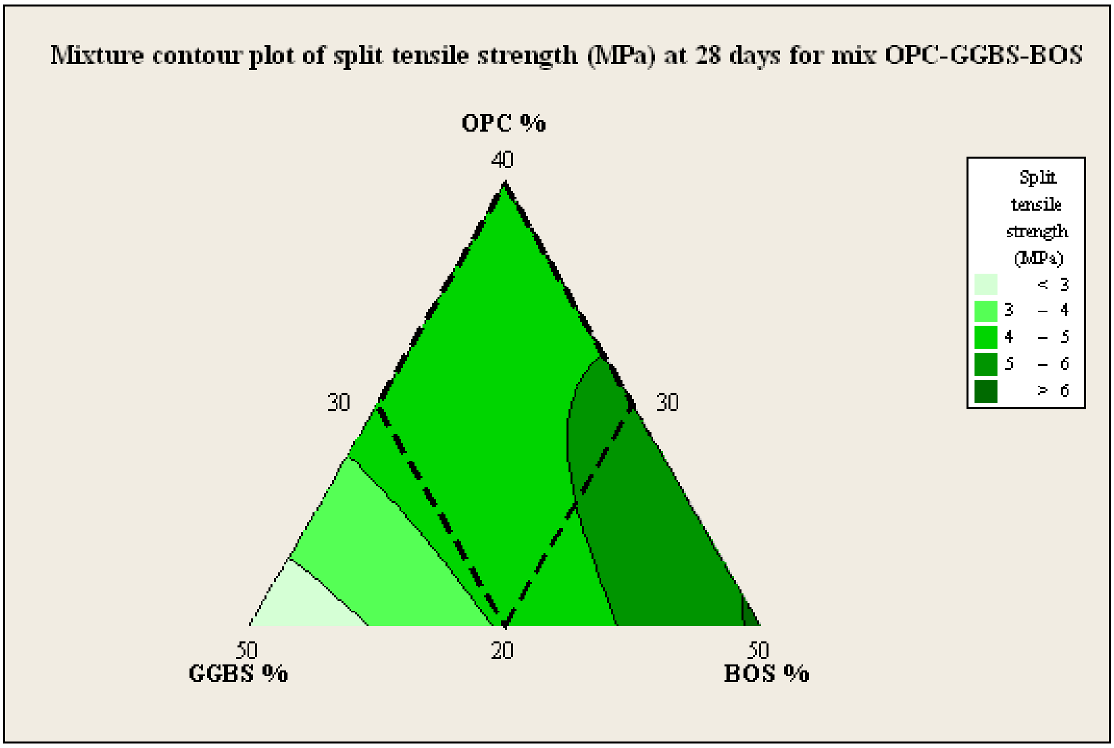


Figure 6.6: Mixture contour plot at 28 days for mix OPC-GGBS-BOS

The 3 dimensional surface plot of the split tensile strength for the OPC-GGBS-BOS mix group is shown at 28 days in Figure 6.7. The effect of OPC on split tensile strength depends on the amount of GGBS and BOS. Figure 6.7 shows that mixes made with the same OPC content can achieve both high and low split tensile strengths. Increasing BOS content increases the strength, while increasing GGBS content results in lower strength. The beneficial effect of BOS in the above mix may be due to the formation of complex iron silicate in the cementitious phase.

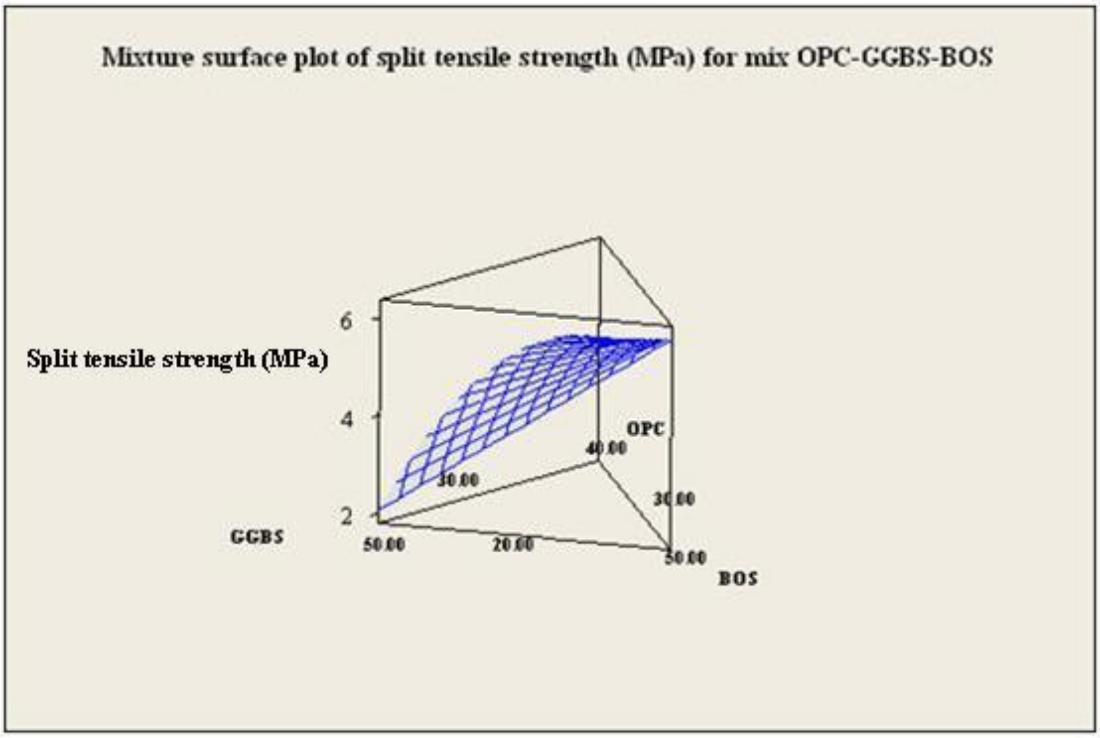


Figure 6.7: Mixture surface plot at 28 days for mix OPC-GGBS-BOS

The quadratic model coefficients were derived by using MINITAB 16 as follows:

Equation 6.12:

$$TS = -0.223\times OPC - 0.221333\times GGBS + 0.208667\times BOS + 0.0113333\times OPC\times GGBS$$

The Equation 6.12 is used for OPC 20-40%, GGBS 30-40% and BOS 30-40%. The results of predicted split tensile strength were obtained by using Equation 6.12. The difference between the predicted and experimental split tensile strength results represents percentage error. The range of percentage error for this group is between 0.0% and 4.4%, this excludes mix 4 which has a percentage error of 9.0 %; this is significantly higher than other mixes in the group. The results in Table 6.6 also indicate that the average percentage error is 3.4%.

Table 6.6: Predicted and average split tensile strength at 28 days for mix OPC-GGBS-BOS

Mix No.	OPC (%)	GGBS (%)	BOS (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	40	30	30	4.3	4.3	0.0
2	30	40	30	4.5	4.3	4.4
3	30	30	40	5.4	5.2	3.7
4	30	35	35	4.4	4.8	9.0
5	20	40	40	4.1	4.1	0.0

Average percentage error of data = 3.4%

R-squared = 80.07%

6.3.2 OPC-BOS-PG

6.3.2.1 Compressive strength of mix OPC-BOS-PG

The mixture design, average compressive strength and predicted compressive strength results for the samples are given in Table 6.7 below.

The simplex design plot for OPC-BOS-PG mixture is shown in Figure 6.8 below. The red point inside the triangle represents the mixes used in this group.

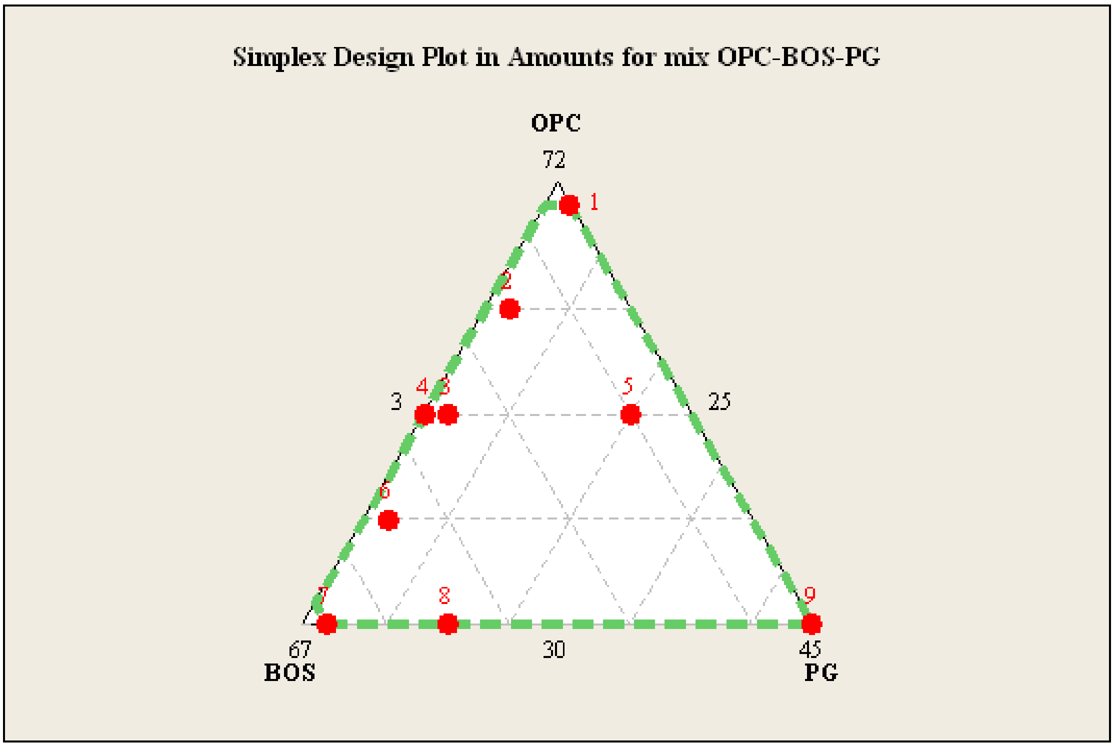


Figure 6.8: Mixture design plot for mix OPC-BOS-PG

The quadratic model coefficients were derived using MINITAB 16 as follows:

Equation 6.13:

$$CS = 0.339433 \times OPC + 0.255611 \times BOS + 1.43604 \times PG + 0.0071355 \times OPC \times BOS - 0.0291671 \times OPC \times PG - 0.0321324 \times BOS \times PG$$

The Equation 6.13 is applicable for OPC 30-70%, BOS 25-65% and PG 3-45%.The

The predicted compressive strength results are presented in Table 6.7 below; the results were obtained by using the Equation 6.13 above. It can be seen that the range of percentage error is between 0.6% and 10.1%; this excludes mixes 2 and 4 as the results for these two mixtures were slightly higher than the other mixes. The overall average percentage error for this specimen is 3.8%.

Table 6.7: Predicted and average compressive strength at 28 days for mix OPC-BOS-PG

Mix No.	OPC (%)	BOS (%)	PG (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	70	25	5	34.4	35.6	3.4
2	60	35	5	40.8	37.1	9.0
3	50	45	5	37.6	37.2	1.0
4	50	47	3	37.4	41.2	10.1
5	50	30	20	15.1	15.6	3.3
6	40	55	5	37.4	35.8	4.2
7	30	65	5	33.3	33.1	0.6
8	30	55	15	17.5	17.9	2.2
9	30	25	45	11.1	11.0	0.9

Average percentage error of data = 3.8%

R-squared = 96.91%

6.3.2.2 Split tensile strength of mix OPC-BOS-PG

The mixture design, average split tensile strength and predicted split tensile strength results are given in Table 6.8 below.

The mixture contour plot of split tensile strength for OPC-BOS-PG mix is presented in Figure 6.9 below. The figure indicates that the optimum percentage of each component from the ternary mix to give the highest split tensile strength is 60% OPC, 35% BOS and 5% PG. The experimental result confirmed this and a split tensile strength result of 5.1 MPa was obtained.

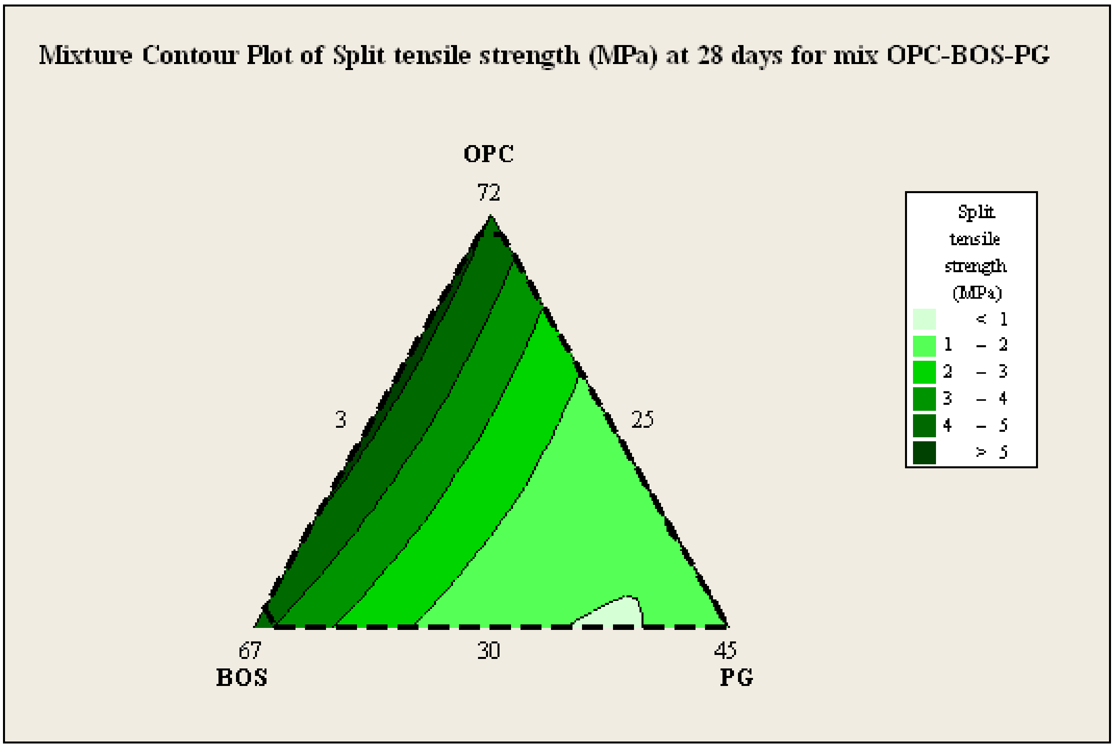


Figure 6.9: Mixture contour plot at 28 days for mix OPC-BOS-PG

The mixture surface plot of split tensile strength for the mix at 28 days is shown in Figure 6.10. The effect of PG is not useful to this mix. It can be seen that mixes containing BOS and OPC only had the highest split tensile strength; this is similar to the trend observed in Figures 5.23 and 6.15.

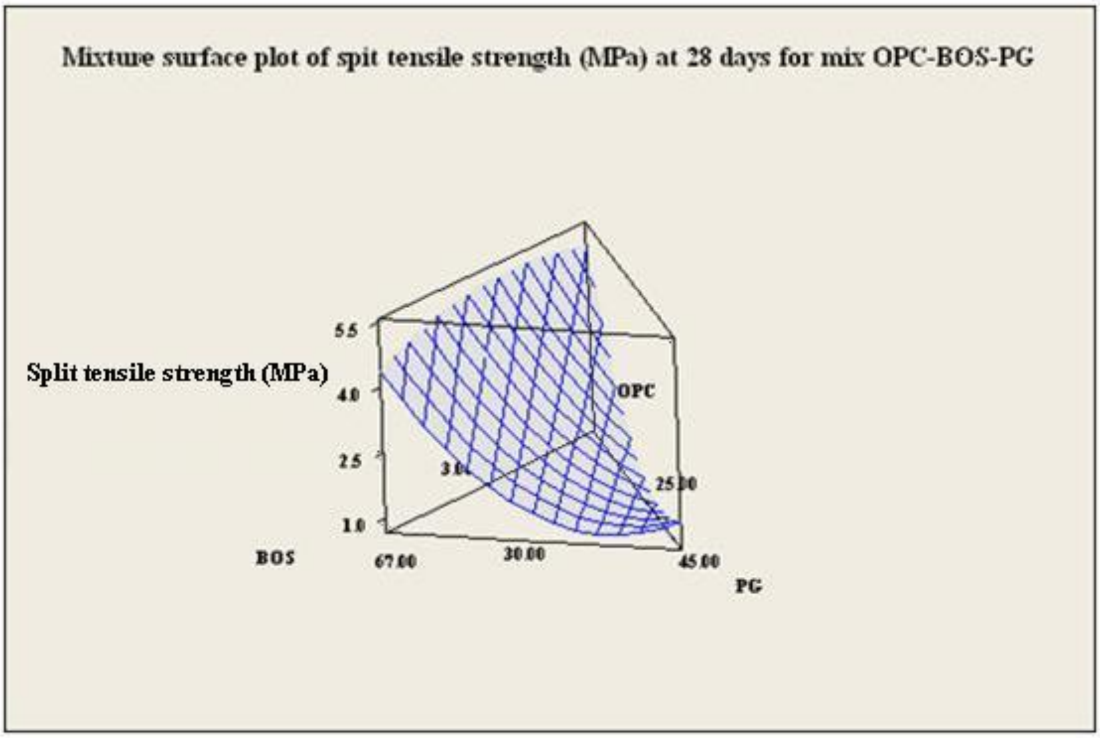


Figure 6.10: Mixture surface plot at 28 days for mix OPC-BOS-PG

The quadratic model coefficients are derived using MINITAB 16:

Equation 6.14:

$$TS = 0.0394934 \times OPC + 0.0176694 \times BOS + 0.180045 \times PG$$
$$+ 0.00126988 \times OPC \times BOS - 0.00391191 \times OPC \times PG - 0.00356654 \times BOS \times PG$$

The Equation 6.14 is valid for OPC 30-780%, BOS 25-65% and PG 3-45%.

The predicted split tensile strength results were obtained using the Equation 6.14. The percentage errors between the predicted and experimental split tensile strength results were all very similar (apart for mix 4). The range of percentage error was between 0.0% and 8.3%, the average percentage error for this group is 3.0%.

Table 6.8: Predicted and average tensile strength at 28 days for mix OPC-BOS-PG

Mix No.	OPC (%)	BOS (%)	PG (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	70	25	5	4.4	4.5	2.2
2	60	35	5	5.1	4.8	5.8
3	50	45	5	4.9	4.7	4.0
4	50	47	3	4.8	5.2	8.3
5	50	30	20	1.9	2.0	5.2
6	40	55	5	4.6	4.5	2.1
7	30	65	5	4.0	4.0	0.0
8	30	55	15	2.2	2.2	0.0
9	30	25	45	1.4	1.4	0.0

Average percentage error of data = 3.0%.

R-squared = 97.80%.

6.3.3 OPC-ROSA-BOS

6.3.3.1 Compressive strength of mix OPC-ROSA-BOS

The mixture design, average compressive strength and predicted compressive strength results for this group are given in Table 6.9 below.

The simplex design plot OPC-ROSA-BOS mix is shown in Figure 6.11 below. The red point inside the triangle represents the mixes used for this mix.

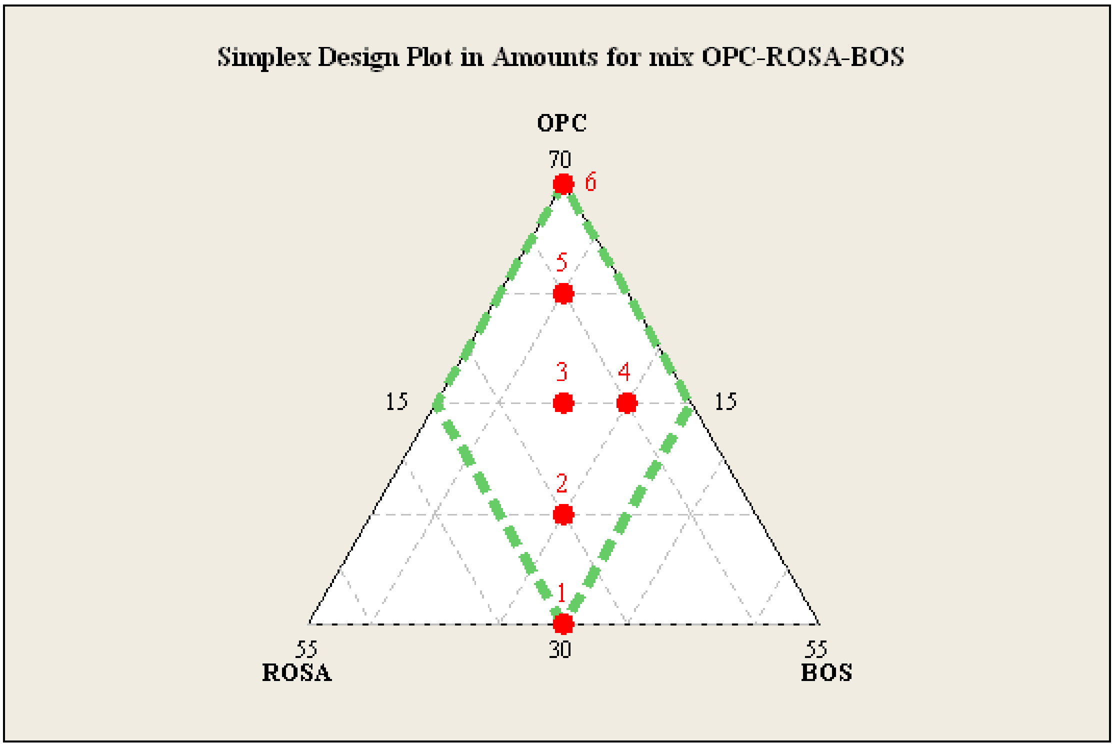


Figure 6.11: Mixture design plot for mix OPC-ROSA-BOS

Quadratic model coefficients were derived using MINITAB 16 software as follows:

Equation 6.15

$$CS = 0.186543\times OPC - 0.536314\times ROSA + 0.2714\times BOS + 0.0278571\times OPC\times ROSA$$

The Equation 6.15 is used for OPC 30-70%, ROSA 15-35% and BOS 15-35%.

The predicted compressive strength results were obtained by using Equation 6.15 and are presented in Table 6.9 below. The percentage error range between the predicted and experimental compressive strength results was between 1.0% and 8.0%, however mixes 3 and 4 are excluded from this range as they had a much higher percentage error than the other mixes. The average percentage error (excluding mix 3 and 4) was 4.6%.

Table 6.9: Predicted and average compressive strength at 28 days for mix OPC-ROSA-BOS

Mix No.	OPC (%)	ROSA (%)	BOS (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	30	35	35	25.1	25.5	1.5
2	40	30	30	34.8	32.9	5.4
3	50	20	30	34.6	31.8	8.0
4	50	25	25	34.8	37.5	7.7
5	60	20	20	41.1	39.3	4.3
6	70	15	15	37.9	38.3	1.0

Average percentage error of data = 4.6%

R-squared = 89.92%

6.3.3.2 Split tensile strength of mix OPC-ROSA-BOS

The mixture design, average split tensile strength and predicted split tensile strength results are given in table 6.10 below.

Figure 6.12 shows the mixture contour plot of split tensile strength for the OPC-ROSA-BOS mix and it was presented by using Minitab 16 software to predict the optimum mixture. This figure indicates that the actual optimization results for this group to give the highest split tensile strength was 52% OPC, 30% ROSA and 18%

BOS. The experimental result confirmed this and the maximum split tensile strength result was 5.14 MPa after 28 days.

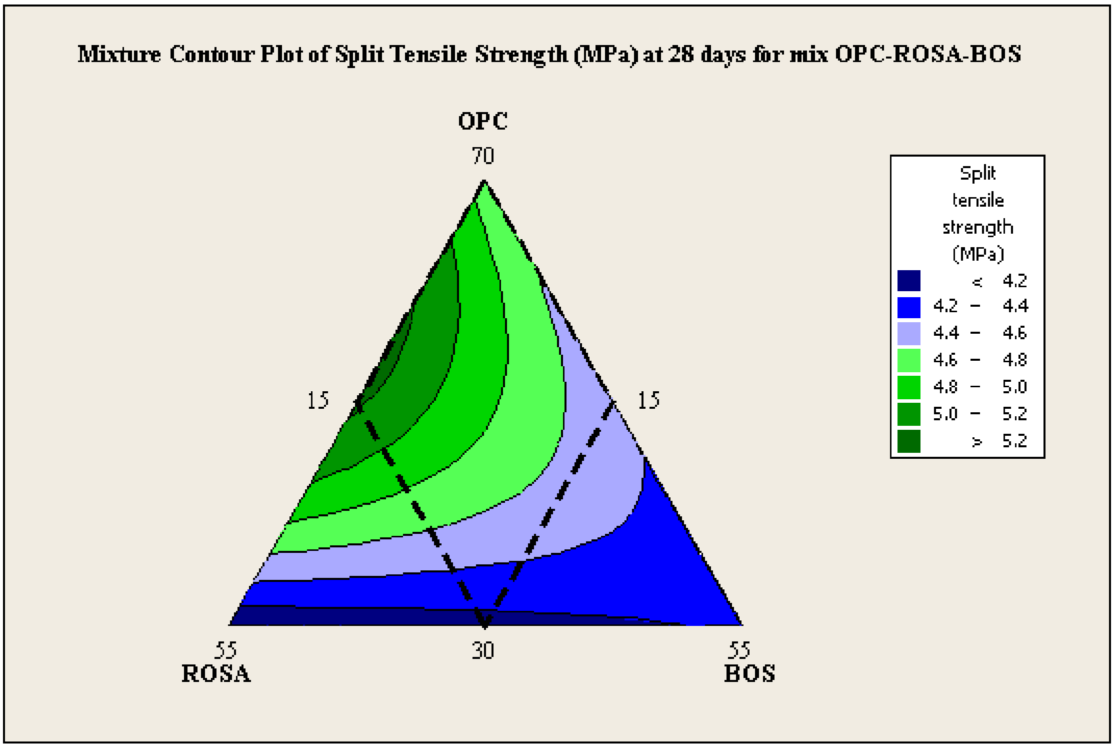


Figure 6.12: Mixture contour plot at 28 days for mix OPC-ROSA-BOS

The mixture surface plot of split tensile strength measured on blocks made with OPC-ROSA-BOS mix at 28 days is presented in Figure 6.13 below. In comparison to BOS, the effect of ROSA is more significant. This may be due to the higher aluminum content in ROSA, as shown in Table 7.1 and 7.2, which forms aluminum silicate phase. Chemical analysis of the mixes showed that the total alkalinity was similar in both mixes.

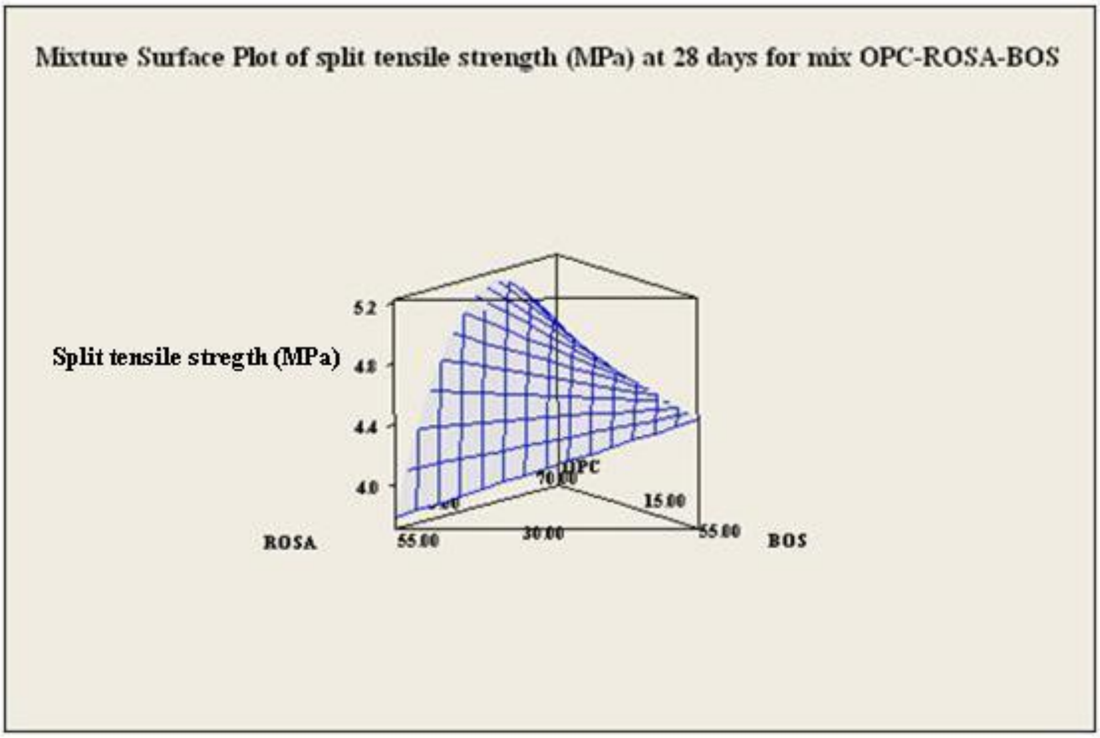


Figure 6.13: Mixture surface plot at 28 days for mix OPC-ROSA-BOS

The quadratic model coefficients were derived using MINITAB 16 software as follows:

Equation 6.16:

$$TS = 0.0290571 \times OPC - 0.0260857 \times ROSA + 0.0542 \times BOS + 0.00214286 \times OPC \times ROSA$$

The Equation 6.16 is applicable for OPC 30-70%, ROSA 15-35% and BOS 15-35%. The predicted split tensile strength was calculated using Equation 6.16 and is given in Table 6.10 below. The table shows that the percentage error between predicted and experimental split tensile strength results are quite small, the range of percentage error is between 0.5% and 1.2% whilst the overall average percentage error for this mix was 0.8%.

Table 6.10: Predicted and average tensile strength at 28 days for mix OPC-ROSA-BOS

Mix No.	OPC (%)	ROSA (%)	BOS (%)	Average tensile strength (MPa) at 28 days	Predicted tensile strength (MPa)	Error (%)
1	30	35	35	4.13	4.11	0.5
2	40	30	30	4.60	4.58	0.4
3	50	25	25	4.79	4.83	0.8
4	60	20	20	4.94	4.88	1.2
5	70	15	15	4.67	4.71	0.9
6	50	20	30	4.65	4.70	1.1

Average percentage error of data = 0.8%

R-squared = 98.01%

6.3.4 OPC-ROSA-PG

6.3.4.1 Compressive strength of mix OPC-ROSA-PG

The mixture design, average compressive strength and predicted compressive strength are given in Table 6.11 below.

Figure 6.14 presents the simplex design plot for OPC-ROSA-PG mix. The red points inside the triangle represent the mixes used for this group.

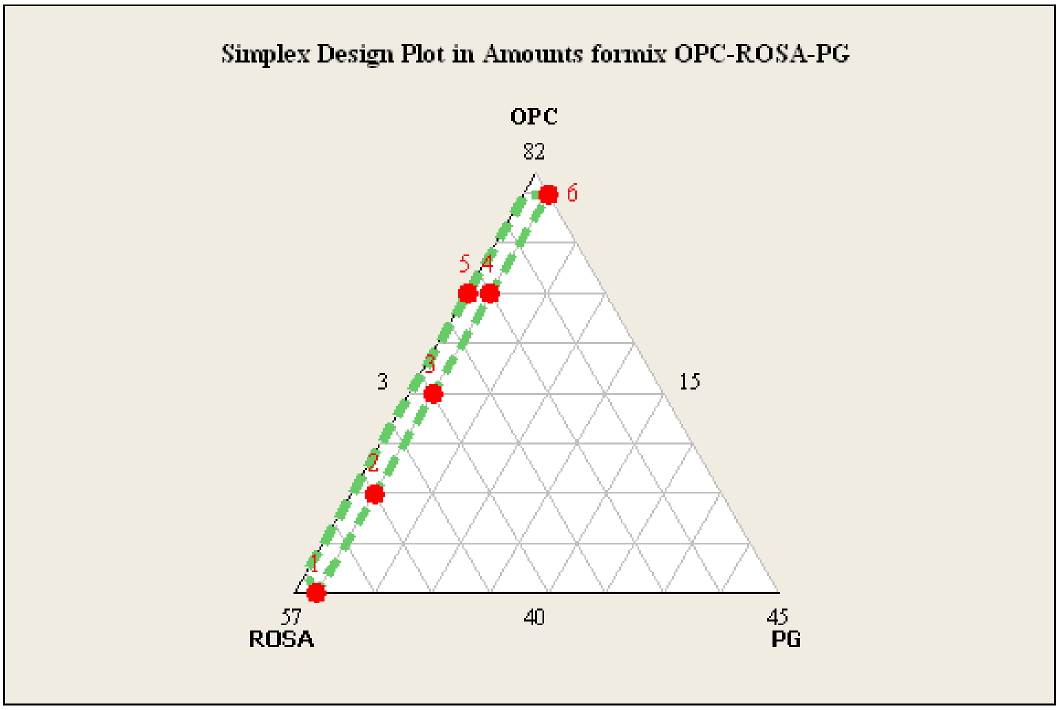


Figure 6.14: Mixture design plot for mix OPC-ROSA-PG

Quadratic model coefficients were derived using MINITAB 16:

Equation 6.17

CS = 0.4315×OPC + 0.0795×ROSA - 1.1505×PG + 4.00047E-18×OPC×ROSA

The Equation 6.17 is applicable for OPC 40-80%, ROSA 15-55% and PG 3-5%.

The predicted compressive strength results were obtained by using Equation 6.17 and are presented in Table 6.11 below. Results show that the percentage error range between predicted and experimental compressive strength results are between 0.0% and 8.4%, and mix 2 showed the highest percentage error. Furthermore, the percentage error average for this mix is 3.9%.

Table 6.11: Predicted and average compressive strength at 28 days for mix OPC-ROSA-PG

Mix No.	OPC (%)	ROSA (%)	PG (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	40	55	5	15.0	15.8	5.3
2	50	45	5	21.2	19.4	8.4
3	60	35	5	22.8	22.9	0.4
4	70	25	5	24.7	26.4	6.8
5	70	27	3	28.9	28.9	0.0
6	80	15	5	30.7	29.9	2.6

Average percentage error of data = 3.9%

R-squared = 95.39%

6.3.4.2 Split tensile strength of mix OPC-ROSA-PG

The mixture design, average split tensile strength and predicted split tensile strength are given in Table 6.12 below.

The mixture contour plot of split tensile strength for OPC-ROSA-PG mix is shown in Figure 6-15 below. The figure shows that 80% OPC, 17% ROSA and 3% PG gave the optimum percentage for the ternary mixture and gave a split tensile strength result of 4.03 MPa.

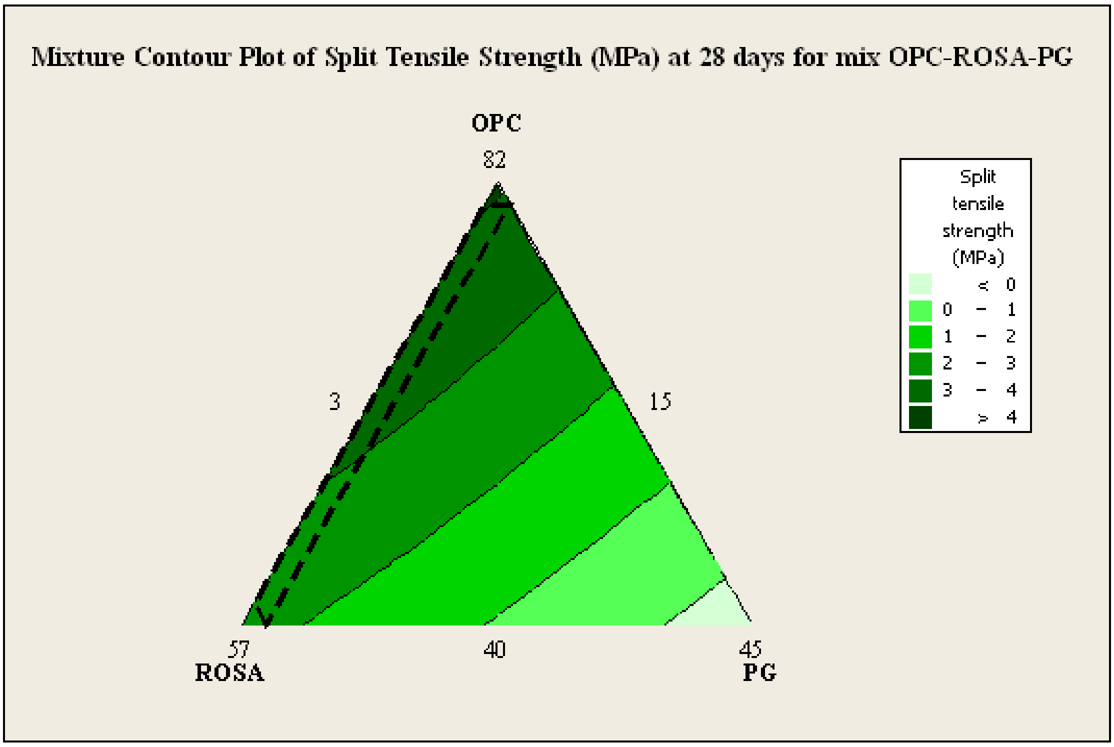


Figure 6.15: Mixture contour plot at 28 days for mix OPC-ROSA-PG

Figure 6.16 presents the mixture surface plot of split tensile strength for the OPC-ROSA-PG mix at 28 days. The effect of PG content is not significant. It is well documented in literatures that gypsum has little activation effect on Pulverised Fuel Ash. Also, it can be seen that a lower ROSA content in the mix resulted in higher strength.

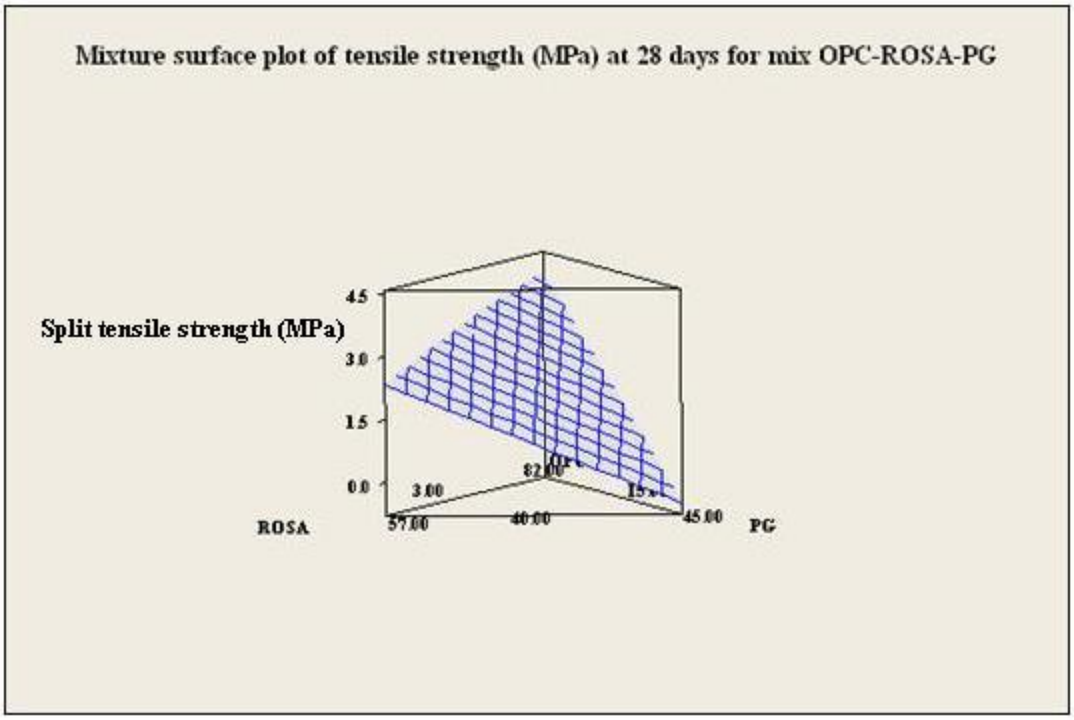


Figure 6.16: Mixture surface plot at 28 days for mix OPC-ROSA-PG

Quadratic model coefficients were derived using MINITAB 16:

Equation 6.18:

$$TS = 0.0480143 \times OPC - 0.00112857 \times ROSA - 0.0568429 \times PG + 0.000285714 \times OPC \times ROSA$$

The Equation 6.18 used for OPC 40-80%, ROSA 15-55% and PG 3-5%.

The predicted split tensile strength was obtained using Equation 6.18 and is given in Table 6.12 below. In this group, the percentage error difference between predicted and experimental tensile strength results were very small, the range of percentage error is between 0.5 and 1.8%. Moreover, the average percentage error for this group is 1.1%.

Table 6.12: Predicted and average split tensile strength at 28 days for mix OPC-ROSA-PG

Mix No.	OPC (%)	ROSA (%)	PG (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	40	55	5	2.23	2.20	1.3
2	50	45	5	2.68	2.71	1.1
3	60	35	5	3.22	3.16	1.8
4	70	25	5	3.51	3.55	1.1
5	70	27	3	3.74	3.70	1.0
6	80	15	5	3.90	3.88	0.5

Average percentage error of data = 1.1%

R-squared = 99.78%

6.3.5 OPC-GGBS-PG

6.3.5.1 Compressive strength of mix OPC-GGBS-PG

The mixture design, average compressive strength and predicted compressive strength are given in Table 6.13 below.

The simplex design plot for mix OPC-GGBS-PG is shown in Figure 6.17 below. The red point inside the triangle represents the mixes used in this group.

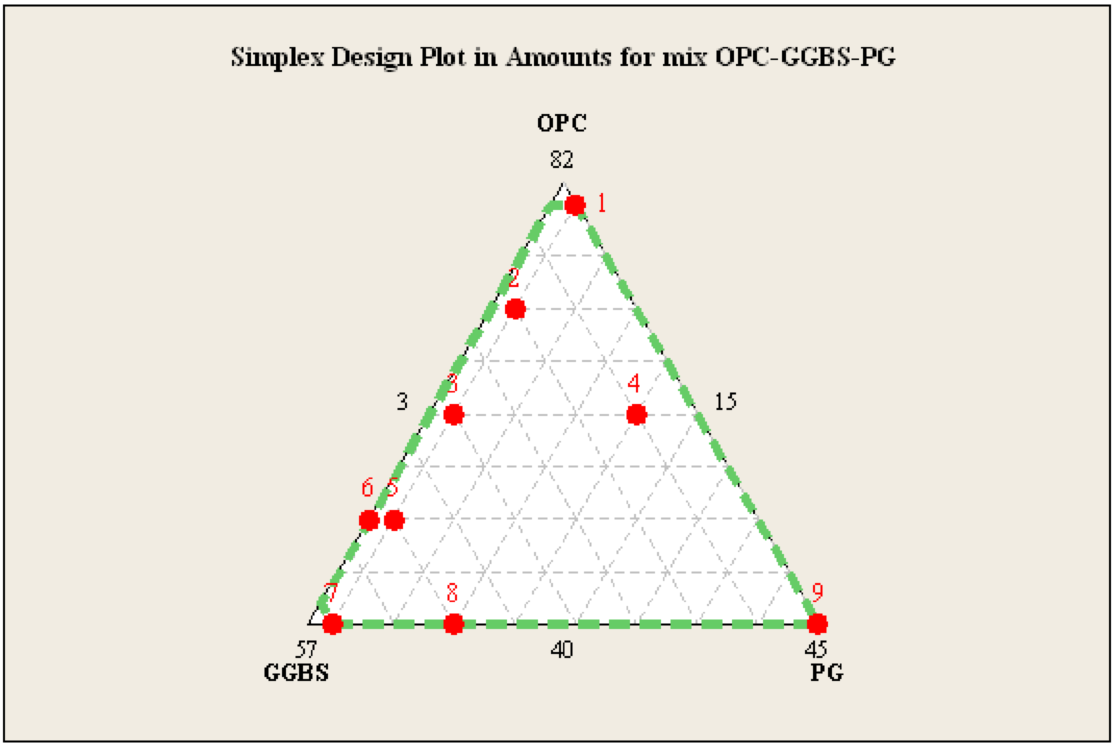


Figure 6.17: Mixture design plot for mix OPC-GGBS-PG

The quadratic model coefficients were obtained using MINITAB 16, as follows:

Equation 6.19

$$CS = 0.203193\times OPC - 0.293791\times GGBS + 0.920689\times PG + 0.0137594\times OPC\times GGBS - 0.0221999\times OPC\times PG - 0.00400847\times GGBS\times PG$$

The Equation 6.19 is applicable for OPC 40-80%, GGBS 15-55% and PG 3-45%.

The predicted compressive strength is presented in Table 6.13 and Equation 6.19 was used to produce the data. The percentage error range of predicted and experimental compressive strength results was between 0.0% and 11.4% whilst the overall percentage error average for this group was 4.3%.

Table 6.13: Predicted and average compressive strength at 28 days for mix OPC-GGBS-PG

Mix No.	OPC (%)	GGBS (%)	PG (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	80	15	5	22.1	23.7	7.2
2	70	25	5	30.7	27.2	11.4
3	60	35	5	27.3	28.0	2.5
4	60	20	20	12.9	13.0	0.7
5	50	45	5	24.7	26.0	5.2
6	50	47	3	26.3	27.5	4.5
7	40	55	5	22.8	21.3	6.5
8	40	45	15	17.2	17.4	1.1
9	40	15	45	10.7	10.7	0.0

Average percentage error of data = 4.3%

R-squared = 94.44%

6.3.5.2 Split tensile strength of mix OPC-GGBS-PG

The mixture design, average split tensile strength and predicted split tensile strength are given in Table 6.14 below.

Figure 6.18 shows the mixture contour plot of split tensile strength for the OPC-GGBS-PG mix. This figure indicates that 70% OPC, 25% GGBS and 5% PG gave the optimum percentages for this mix to produce the highest split tensile strength. The experimental result confirmed this and showed that at above mix achieved tensile strength result of 4.4 MPa.

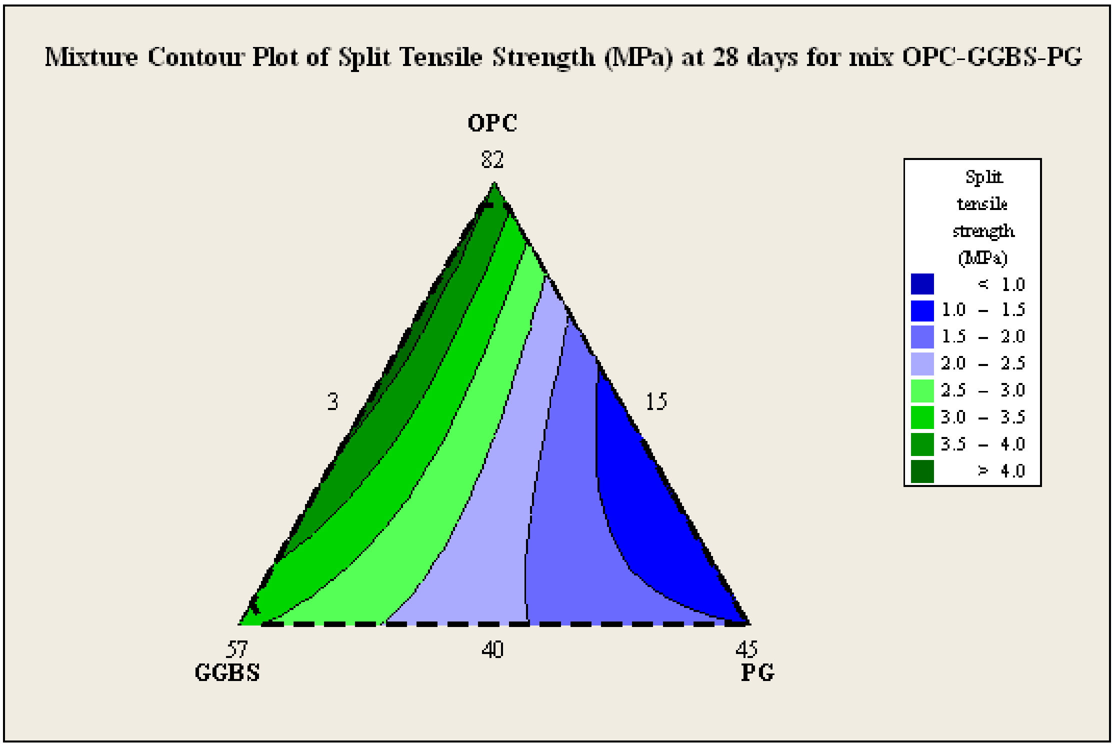


Figure 6.18: Mixture contour plot at 28 days for mix OPC-GGBS-PG

The mixture surface plot of split tensile strength for the OPC-GGBS-PG mix at 28 days is presented in Figure 6.19 below. The effect of PG content on split tensile strength was insignificant and showed the same trend as other mixes containing PG presented in sections 6.3.2, 6.3.4 and 6.3.5. Furthermore, results showed that the highest split tensile strength was achieved with GGBS content ranging from 20 to 40%.

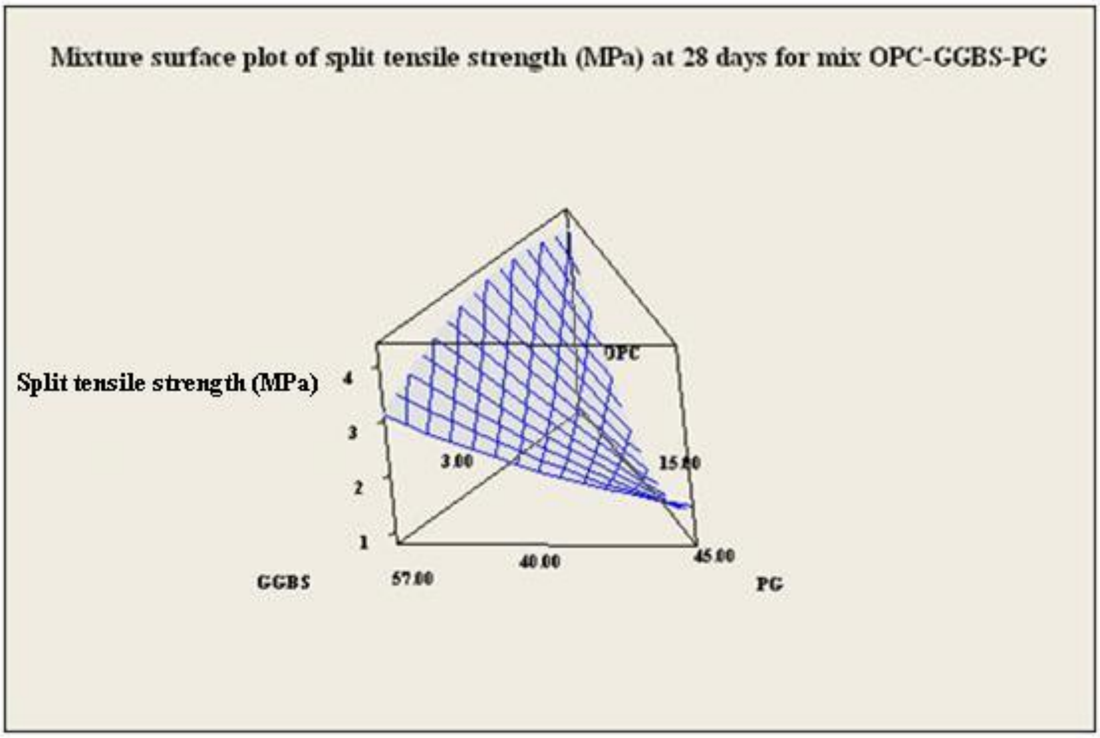


Figure 6.19: Mixture surface plot at 28 days for mix OPC-GGBS-PG

Quadratic model coefficients were derived using MINITAB 16 software:

Equation 6.20:

$$TS = 0.0392960\times OPC - 0.0227872\times GGBS + 0.132857\times PG$$
$$+ 0.00128174\times OPC\times GGBS - 0.00342968\times OPC\times PG - 4.47927E\text{-}04$$

The Equation 6.20 is valid for OPC 40-80%, GGBS 15-55% and PG 3-45%.

The predicted split tensile strength is shown in Table 6.14 below. In this group, the percentage error between predicted and experimental split tensile strength results were spread out between the mixes, the percentage error range is between 2.7% and 20.0%, which is a very wide range. The percentage error average for the group is 9.0%.

Table 6.14: Predicted and average split tensile strength at 28 days for mix OPC-GGBS-PG

Mix No.	OPC (%)	GGBS (%)	PG (%)	Average tensile strength (MPa) at 28 days	Predicted tensile strength (MPa)	Error (%)
1	80	15	5	3.3	3.6	9.0
2	70	25	5	4.4	3.9	11.3
3	60	35	5	3.7	3.8	2.7
4	60	20	20	1.8	1.9	5.5
5	50	45	5	3.4	3.6	5.8
6	50	47	3	3.4	3.7	8.8
7	40	55	5	3.3	3.1	6.0
8	40	45	15	2.4	2.7	12.5
9	40	15	45	1.5	1.8	20.0

Average percentage error of data = 9.0%

R-squared = 89.10%

6.3.6 OPC-ROSA–BPD

6.3.6.1 Compressive strength of mix OPC-ROSA-BPD

The mixture design, average compressive strength and predicted compressive strength results are given in Table 6.15 below.

Figure 6.20 shows the simplex design plot for the OPC-ROSA-BPD mix.

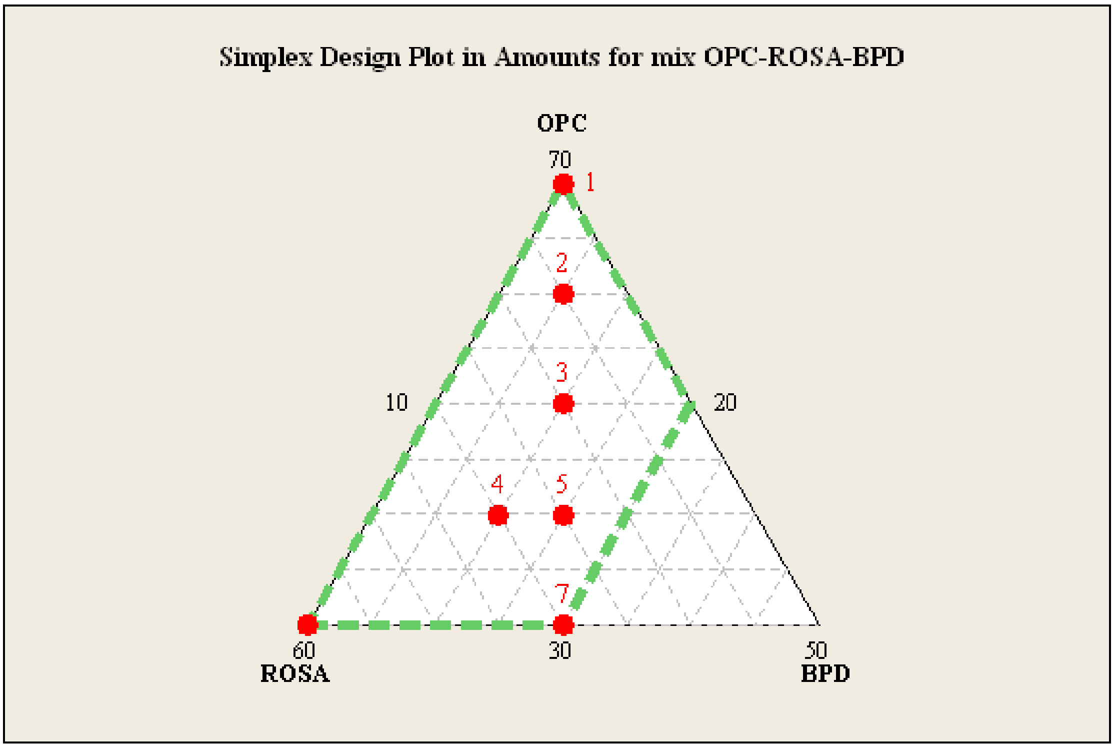


Figure 6.20: Mixture design plot for mix OPC-ROSA-BPD

Quadratic model coefficients were derived using MINITAB 16 software, as follows:

Equation 6.21:

$$CS = 1.05084\times OPC + 0.384643\times ROSA + 0.124757\times BPD - 0.0178914\times OPC\times ROSA - 0.0130229\times OPC\times BPD$$

The Equation 6.21 used for OPC 30-70%, ROSA 20-60% and BPD 10-30%.

The predicted compressive strength was obtained using Equation 6.21 and is presented in Table 6.15 below. The differences in percentage error between predicted and experimental compressive strength results in this group were between 0.0% and 18.4%. The highest difference between predicted and experimental compressive strength was in mix 2 in which higher percentage error was observed. The average percentage error for the group is 6.3%.

Table 6.15: Predicted and average compressive strength at 28 days for mix OPC-ROSA-BPD

Mix No.	OPC (%)	ROSA (%)	BPD (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	70	20	10	50.3	48.3	3.9
2	60	25	15	30.3	35.9	18.4
3	50	30	20	31.7	26.7	15.7
4	40	40	20	20.8	20.87	0.0
5	40	35	25	19.6	20.5	4.5
6	30	60	10	19.7	19.7	0.0
7	30	40	30	17.1	17.4	1.7

Average percentage error of data = 6.3%

R-squared = 92.36%

6.3.6.2 Split tensile strength of mix OPC-ROSA-BPD

The mixture design, average split tensile strength and predicted split tensile strength are given in Table 6.16 below.

The mixture contour plot of split tensile strength for OPC-ROSA-BPD is shown in Figure 6.21 below. This figure indicates that 50% OPC, 40% ROSA and 10% BPD gave the optimum percentage for this mix to produce a split tensile strength result of 4.38 MPa, this is the highest split tensile strength obtained for this mix.

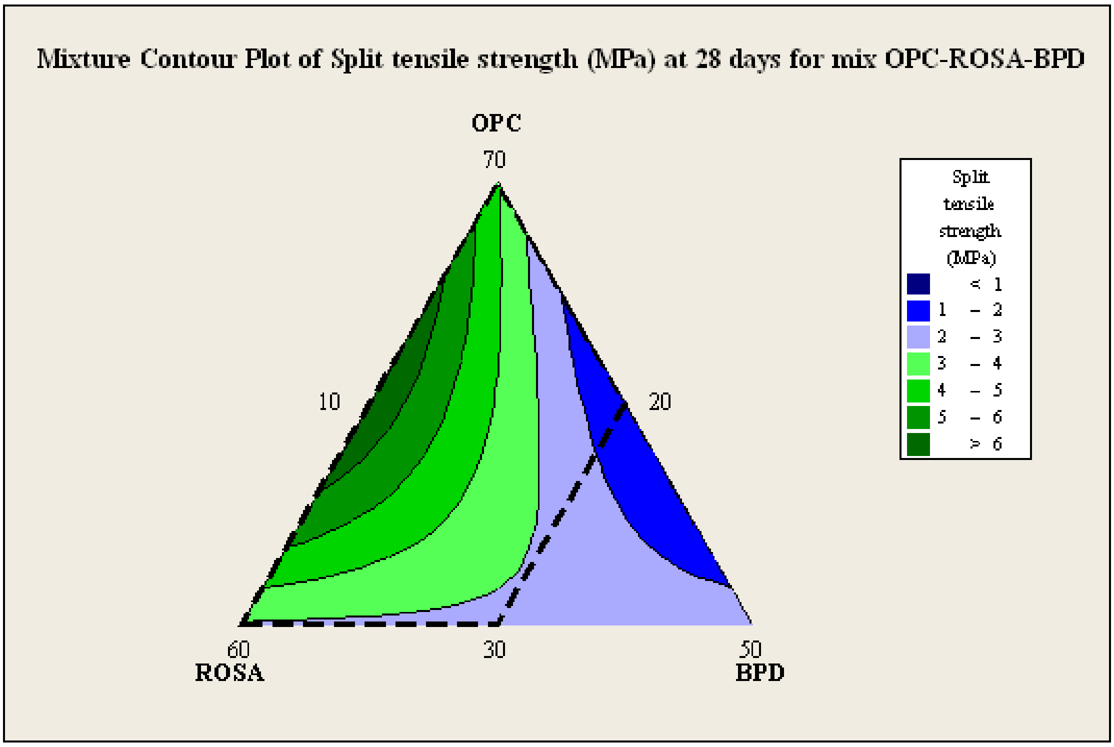


Figure 6.21: Mixture contour plot at 28 days for mix OPC-ROSA-BPD

Figure 6.22 illustrates the mixture surface plot of split tensile strength for blocks of OPC-ROSA-BPD mix at 28 days. The effect of BPD content on split tensile strength is not significant. The figure shows that as BPD increases to more than 20%, the strength is reduced. When mixes had 20-50% ROSA content, a higher split tensile strength was observed, whilst increasing BPD content reduced strength.

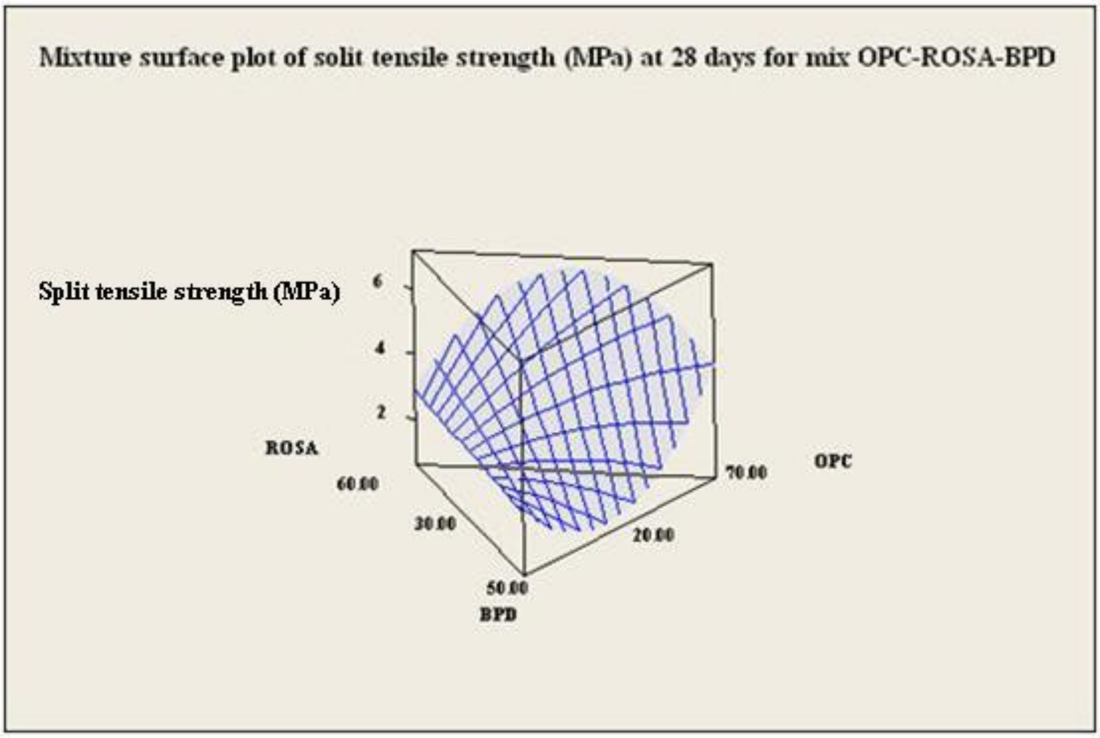


Figure 6.22: Mixture surface plot at 28 days for mix OPC-ROSA-BPD

The quadratic model coefficients were derived using MINITAB 16 software, as follows:

Equation 6.22:

$$TS = -\ 0.0239243\times OPC - 0.192474\times ROSA + 0.216154\times BPD + 0.00818214\times OPC\times ROSA - 0.00571071\times OPC\times BPD$$

The Equation 6.22 is valid for OPC 30-70%, ROSA 20-60% and BPD 10-30%.

The predicted split tensile strength was worked out using Equation 6.22; the results are presented in Table 6.16 below. The average percentage error is 4.2% for this mix. The range in percentage error is between 0.0% and 13.8%. Mix 2 has a significantly higher percentage error than the other mixes.

Table 6.16: Predicted and average split tensile strength at 28 days for mix OPC-ROSA-BPD

Mix No.	OPC (%)	ROSA (%)	BPD (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	70	20	10	4.3	4.1	4.6
2	60	25	15	3.6	4.1	13.8
3	50	30	20	4.1	3.9	4.8
4	40	40	20	4.2	4.2	0.0
5	40	35	25	3.6	3.5	2.7
6	30	60	10	2.9	2.9	0.0
7	30	40	30	2.6	2.7	3.8

Average percentage error of data = 4.2%

R-squared = 84.25%

6.3.7 OPC-GGBS-BPD

6.3.7.1 Compressive strength of mix OPC-GGBS-BPD

The mixture design, average compressive strength and predicted compressive strength are given in Table 6.17 below.

The simplex design plot in amounts for OPC-GGBS-BPD mix is shown in Figure 6.23 below. The red point inside the triangle symbolizes the mixes used in this group.

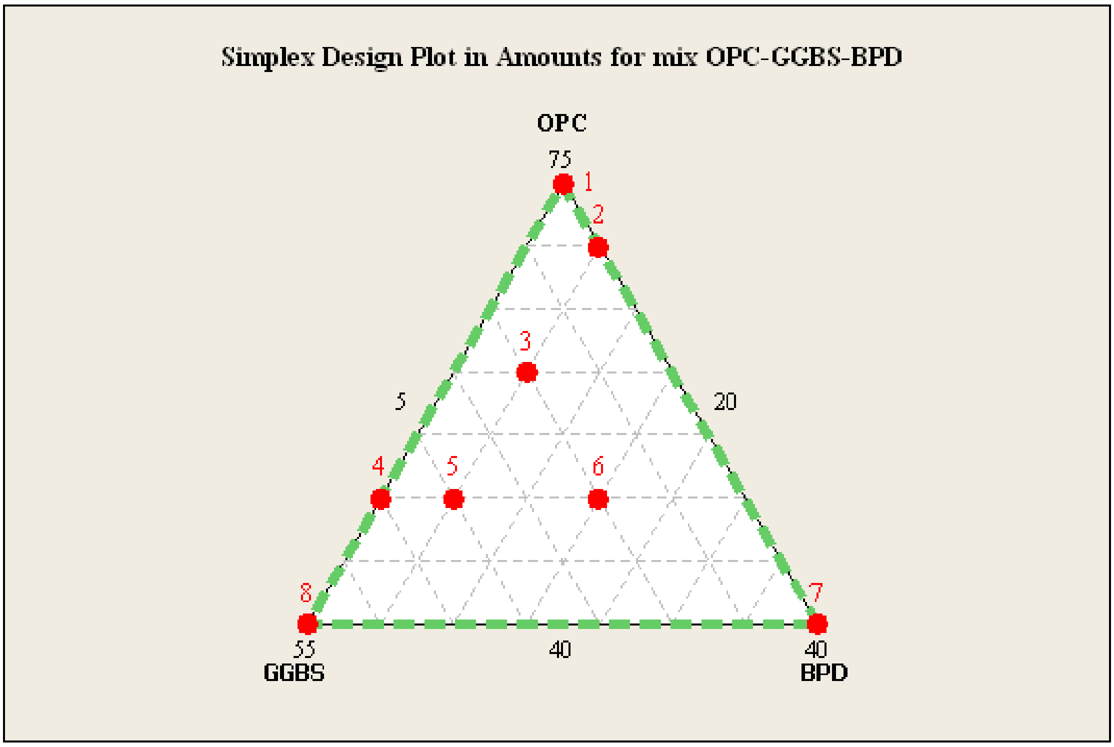


Figure 6.23: Mixture design plot for mix OPC-GGBS-BPD

Quadratic model coefficients were derived using MINITAB 16:

Equation 6.23:

$$CS = 0.877828 \times OPC + 0.488557 \times GGBS + 2.98243 \times BPD - 0.00824283 \times OPC \times GGBS - 0.0724696 \times OPC \times BPD - 0.0342571 \times GGBS \times BPD$$

The Equation 6.23 used for OPC 40-75%, GGBS 20-45% and BPD 5-40%.

The predicted compressive strength is presented in Table 6.17 below. A wide range of percentage error can be seen, the results range from 0.5% to 24%. The average percentage error is calculated to be 8.5%.

Table 6.17: Predicted and average compressive strength at 28 days for mix OPC-GGBS-BPD

Mix No.	OPC (%)	GGBS (%)	BPD (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	75	20	5	48.7	47.6	2.2
2	70	20	10	30.4	31.9	4.9
3	60	30	10	27.8	28.5	2.5
4	50	45	5	39.7	36.4	8.3
5	50	40	10	21.6	26.8	24.0
6	50	30	20	16.5	12.8	22.4
7	40	20	40	13.7	14.2	3.6
8	40	55	5	34.6	34.8	0.5

Average percentage error of data = 8.5%

R-squared = 94.12%

6.3.7.2 Split tensile strength of mix OPC-GGBS-BPD

The mixture design, average split tensile strength and predicted split tensile strength are given in Table 6.18 below.

Figure 6.24 shows the mixture contour plot of split tensile strength optimization for the OPC-GGBS-BPD mix. It can be seen that this figure indicates 75% OPC, 20% GGBS and 5% BPD gave the optimum percentages for this mix to achieve the maximum split tensile strength. The experimental result confirmed this and showed that at these percentages a split tensile strength result was 5.9 MPa.

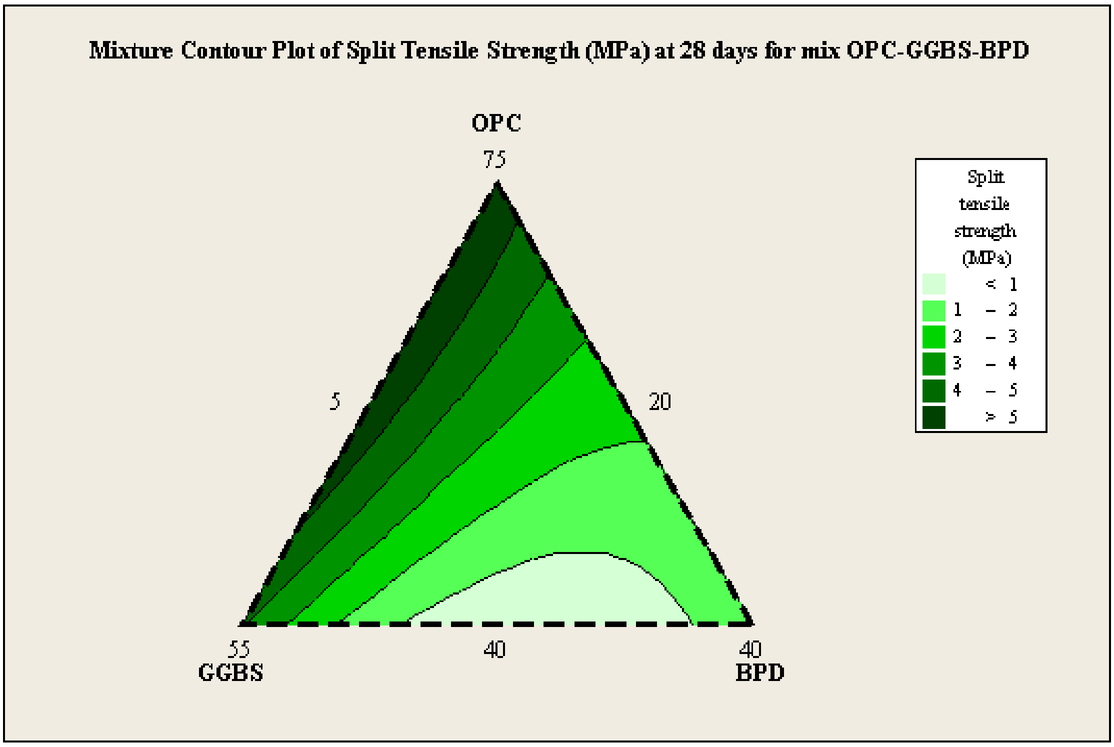


Figure 6.24: Mixture contour plot at 28 days for mix OPC-GGBS-BPD

Figure 6.25 presents the mixture surface plot of split tensile strength for blocks of OPC-GGBS-BPD mix at 28 days. The effect of BPD content on split tensile strength is relatively significant. Results indicated that as the percentage of BPD is increased to 10% or higher, the strength decreases, whereas as GGBS content was between 20-45% a high split tensile strength result was recorded. Mixes with high BPD content and low strength may have occurred due to the effect of high alkalinity in the mix.

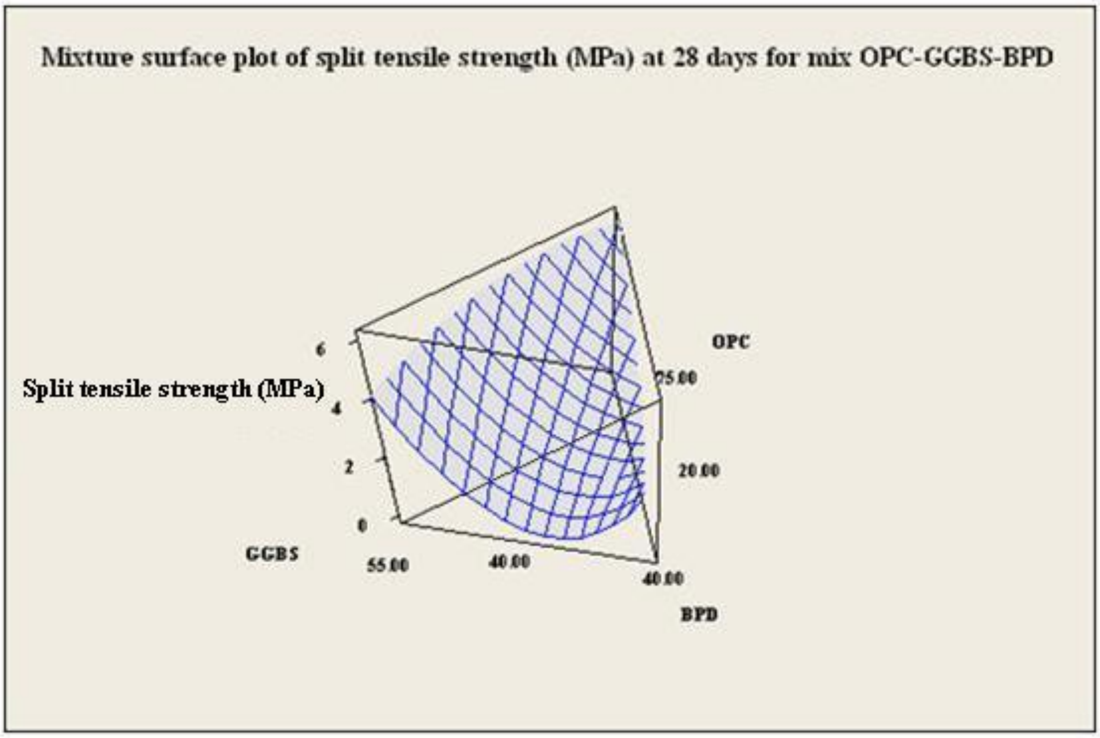


Figure 6.25: Mixture surface plot at 28 days for mix OPC-GGBS-BPD

Quadratic model coefficients were derived using MINITAB 16:

Equation 6.24

$$TS = 0.0462549\times OPC - 0.0367480\times GGBS + 0.349998\times BPD + 0.00274321\times OPC\times GGBS - 0.00506889\times OPC\times BPD - 0.00911979\times GGBS\times BPD$$

The Equation 6.24 is used for OPC 40-75%, GGBS 20-45% and BPD 5-40%. The predicted split tensile strength is presented in Table 6-18 below; Equation 6.24 was used to obtain these results. The table also shows that the range of percentage error varies from 1.6% to 22.7% whilst the average percentage error for this group was found to be 8.5%.

Table 6.18: Predicted and average tensile strength at 28 days for mix OPC-GGBS-BPD

Mix No.	OPC (%)	GGBS (%)	BPD (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	75	20	5	5.9	5.8	1.6
2	70	20	10	4.5	4.4	2.2
3	60	30	10	3.7	4.3	16.2
4	50	45	5	5.8	5.3	8.6
5	50	40	10	3.3	3.6	9.0
6	50	30	20	2.2	1.7	22.7
7	40	20	40	1.8	1.9	5.5
8	40	55	5	3.9	4.0	2.5

Average percentage error of data = 8.5%

R-squared = 92.93%

6.3.8 OPC-BOS –BPD

6.3.8.1 Compressive strength of mix OPC-BOS-BPD

The mixture design, average compressive strength and predicted compressive strength are given in Table 6.19 below.

The simplex design plot in amounts for OPC-BOS-BPD mix is shown in Figure 6.26 below. The red point inside the triangle presents the mixes used in this group.

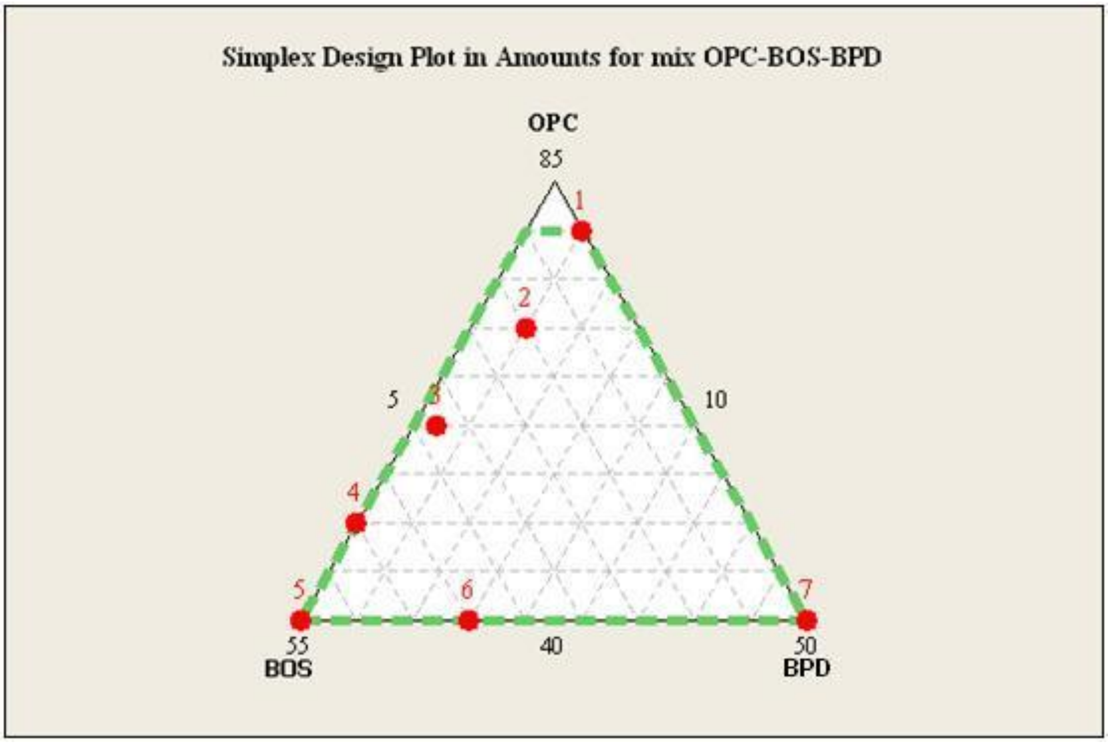


Figure 6.26: Mixture design plot for mix OPC-BOS-BPD

Quadratic model coefficients were derived using MINITAB 16 as follows:

Equation 6.25:

$$CS = -0.548719\times OPC - 4.52298\times BPD + 0.665459\times BOS + 0.132633\times OPC\times BPD + 0.0167188\times OPC\times BOS - 0.0321004\times BPD\times BOS$$

The Equation 6.25 is applicable for OPC 40-80%, BOS 10-55% and BPD 5-50%.

The predicted compressive strength was obtained by using Equation 6.25 and is presented in Table 6.19 below. It can be seen that percentage error for this group was small and similar (excluding mixes 3 and 4). The percentage error ranges from 0.0% to 5.0% while, and the percentage error average is calculated to be 1.8% for this group.

Table 6.19: Predicted and average compressive strength at 28 days for mix OPC-BOS-BPD

Mix No.	OPC (%)	BOS (%)	BPD (%)	Average compressive strength (MPa) at 28 days	Predicted compressive strength (MPa)	Error (%)
1	80	10	10	33.6	33.8	0.5
2	70	20	10	39.3	39.5	0.5
3	60	33	7	40.6	38.8	4.4
4	50	45	5	41.3	43.4	5.0
5	40	55	5	47.4	46.5	1.8
6	40	10	50	14.5	14.5	0.0
7	40	40	20	21.2	21.3	0.4

Average percentage error of data = 1.8%

R-squared = 98.97%

6.3.8.2 Split tensile strength of mix OPC-BOS-BPD

The mixture design, average split tensile strength and predicted split tensile strength are given in Table 6.20 below.

Figure 6.27 shows the mixture contour plot of split tensile strength for the OPC-BOS-BPD mix. This figure indicates that 40% OPC, 55% BOS and 5% BPD gave the optimum percentages for this mix to produce the highest split tensile strength which was 5.16 MPa.

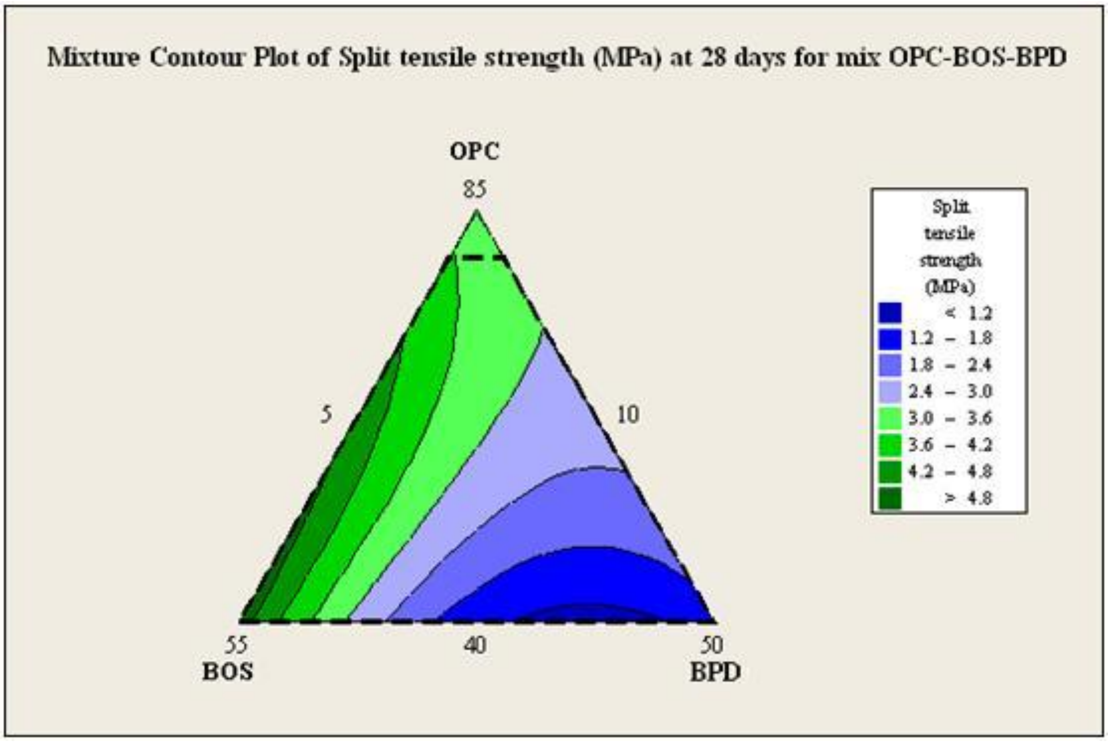


Figure 6.27: Mixture contour plot at 28 days for mix OPC-BOS-BPD

The mixture surface plot of split tensile strength for blocks of OPC-BOS-BPD mix at 28 days is presented in Figure 6.28 below. The effect of BPD content on split tensile strength is significant and as the percentage of BPD increases to more than 7% the strength decreases. Also, the effect of BOS content on split tensile strength is significant and as the BOS content increases the strength also increases. The highest strength achieved with BOS ranged from 40-55%.

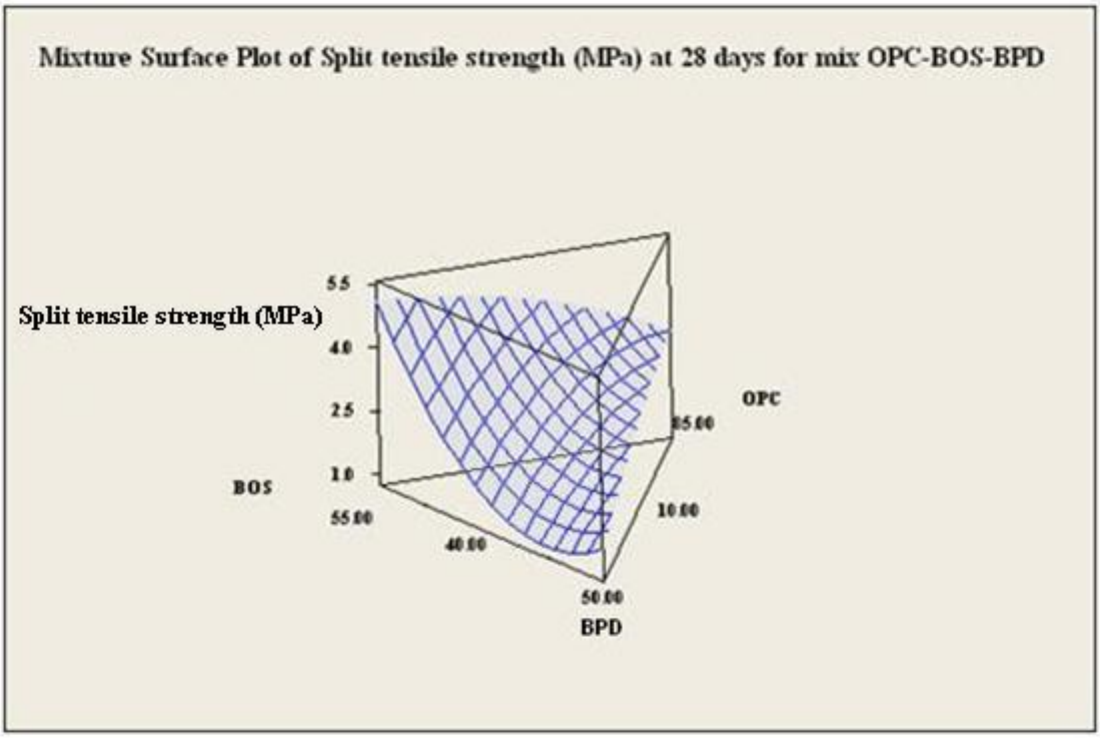


Figure 6.28: Mixture surface plot at 28 days for mix OPC-BOS-BPD

Quadratic model coefficients were derived using MINITAB 16 as follows:

Equation 6.26:

$$TS = 0.022547\times OPC + 0.0586693\times BOS + 0.0107548\times BPD + 0.000826764\times OPC\times BOS + 0.000508911\times OPC\times BPD - 0.00371295\times BOS\times BPD$$

The Equation 6.26 is valid for OPC 40-80%, BOS 10-55% and BPD 5-50%.

The predicted split tensile strength is presented in Table 6.20 below and was obtained using Equation 6.26. The table shows that the percentage error values were small for this mix (excluding mix 3 and 4) and the range of values varied from 0.0% and 3.7% whilst the percentage error average was 1.4%.

Table 6.20: Predicted and average split tensile strength at 28 days for mix OPC-BOS-BPD

Mix No.	OPC (%)	BOS (%)	BPD (%)	Average split tensile strength (MPa) at 28 days	Predicted split tensile strength (MPa)	Error (%)
1	80	10	10	3.18	3.20	0.6
2	70	20	10	3.61	3.63	0.5
3	60	33	7	4.51	4.36	3.3
4	50	45	5	4.79	4.97	3.7
5	40	55	5	5.16	5.08	1.5
6	40	10	50	1.52	1.52	0.0
7	40	40	20	2.21	2.22	0.4

Average percentage error of data = 1.4%

R-squared = 99.43%.

6.3.9 Summary of optimum mixes from phase1:

Figure 6.29 summarizes the split tensile strength all optimum mixes at 28 days for the second phase; in this phase only seven mixes with the highest strength were selected. It can be seen from Figure 6.29 that mix OPC50-GGBS45-BPD5 gave the highest strength in comparison to other mixes in the same phase.

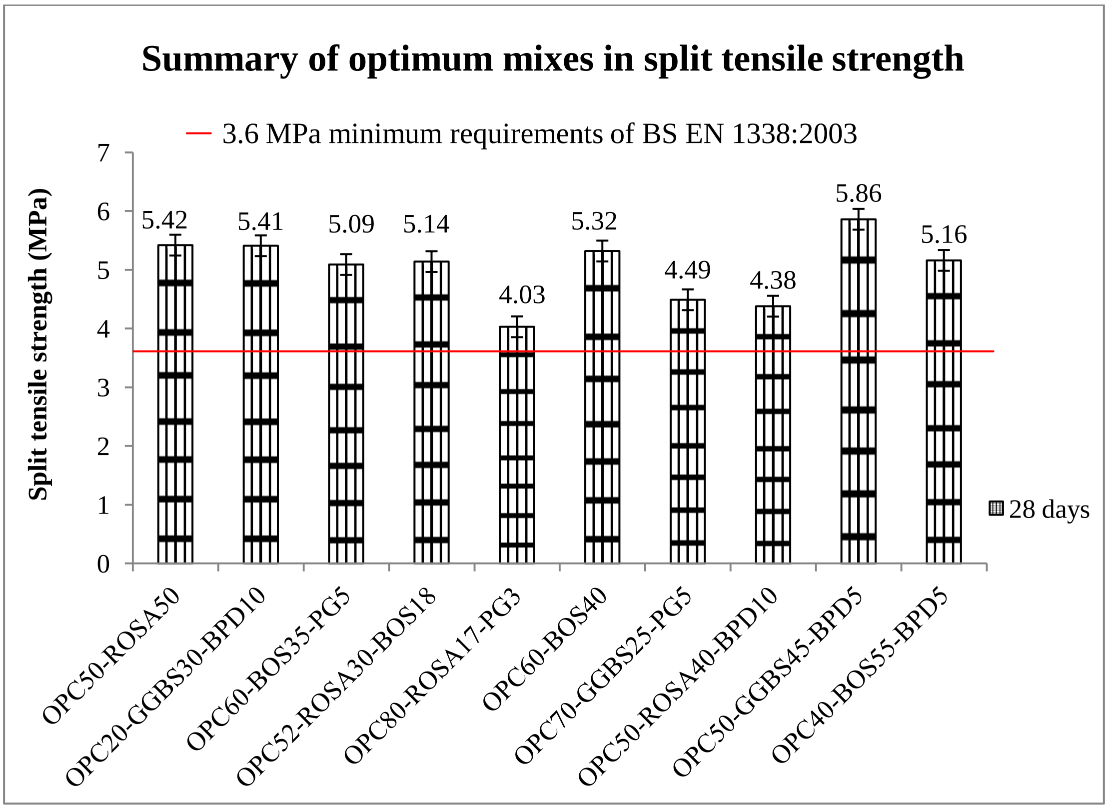


Figure 6.29: The summary of optimum mixes in split tensile strength of paving blocks at 28 days

7. Chemical analysis

7.1 Chemical analysis of raw materials

Chemical analysis of the raw materials used was determined using X-ray fluorescence (XRF) method. These are shown in Table 7.1.

Table 7.1 shows that for all raw materials, the silica content varies depending on the materials used, it should be noted that a high silica content increase the strength of mixes. Furthermore, it can be seen that ROSA and GGBS were the promising specimens as they had the highest percentage of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) in comparison to other materials. Alternatively, Table 7.1 shows that BPD has the highest amount of alkalis in comparison to other raw materials; therefore, the BPD used should be limited in order to prevent any reduction in strength caused by an increase in alkali.

On the other hand, the GGBS is a well-known pozzolan and when water is added to GGBS, it displays similar characteristics to cement; therefore, GGBS was used in this research as a cement substitute. Furthermore, ROSA can also be considered as a pozzolanic material, as can be seen from Table 7.1, the total SiO_2+Al_2O_3+ Fe_2O_3 is 77.65%, which is higher than 70.0% and classified as class N according to ASTM C618-12a. Moreover, BOS has some pozzolanic properties as the CaO content is high, around 42.0%, and the total of SiO_2+Al_2O_3+ Fe_2O_3 is 41.27%, therefore for this reason BOS was also used in this study to replace cement.

Table 7.1: Chemical content of OPC, BOS, ROSA, PG and PBD used

Sample oxides	OPC (%)	BOS (%)	ROSA (%)	PG (%)	BPD (%)	GGBS (%)
SiO_2	20.00	11.43	45.91	2.43	21.86	37.28
TiO_2	-	0.39	1.41	0.03	0.29	0.58
Al_2O_3	6.00	1.60	26.51	0.81	3.85	10.79
Fe_2O_3	3.00	28.24	5.23	0.36	2.57	0.43
MnO	-	4.35	0.08	< 0.01	0.02	0.68
MgO	1.50	8.27	2.13	0.40	1.13	8.83
CaO	63.00	41.29	6.88	37.30	53.40	40.12
Na_2O	1.00	0.02	0.61	0.03	0.41	0.27
K_2O	1.00	0.02	1.35	0.24	3.64	0.37
P_2O_5	-	1.48	0.98	0.02	0.08	< 0.05
SO_3	2.00	0.44	1.37	53.07	7.10	0.15
LoI	0.50	3.12	7.11	4.09	5.64	1.03
Total alkalinity ($Na_2O + K_2O$)	2.00	0.04	1.96	0.27	4.05	0.64
$SiO_2+Al_2O_3+CaO$	69.00	54.32	79.30	40.54	79.11	88.19
$SiO_2+Al_2O_3+ Fe_2O_3$	29.00	41.27	77.65	3.60	28.28	48.50

The typical chemical composition of pozzolanic materials, such as pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS) is well understood and their use as cement replacements is well-established in construction and concrete technology (Claisse et al., 2007).

Figure 7.1 and Table 7.1 show the comparative $CaO-Al_2O_3-SiO_2$ content of cementitious materials (OPC, GGBS and PFA), materials and all mixes used in this research. The figure shows that most of the raw materials used are placed near OPC and GGBS. The figure indicates GGBS and by pass dust is more promising to replace OPC.

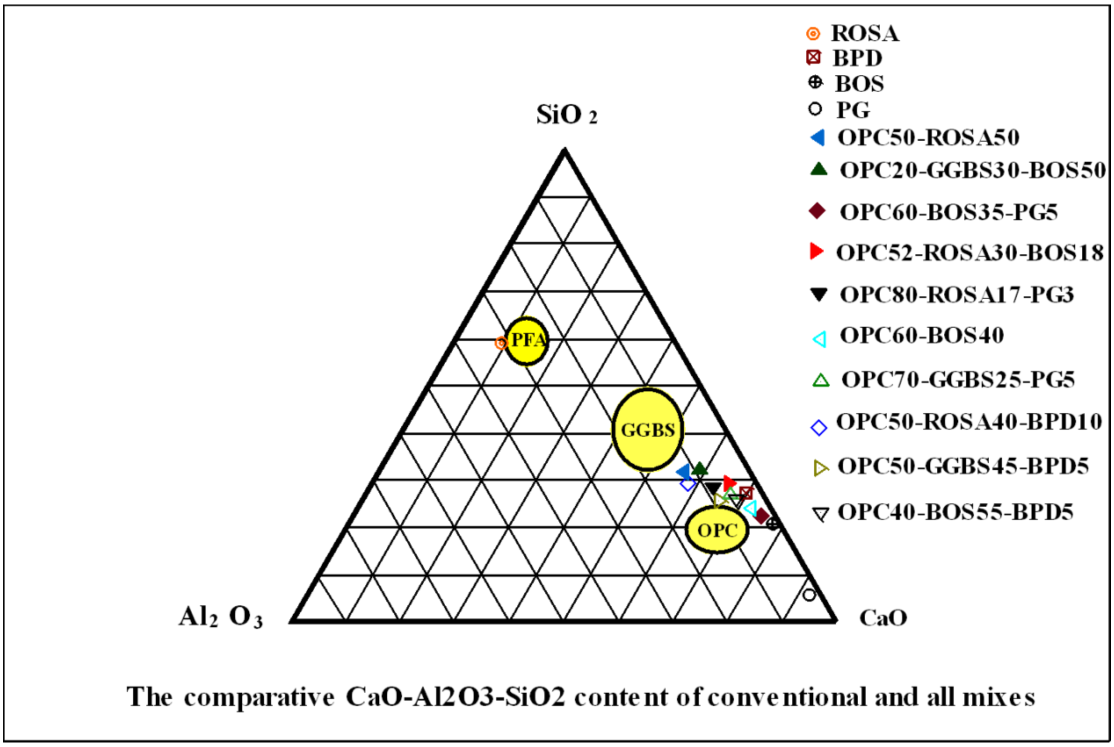


Figure 7.1: The comparative CaO-Al_2O_3-SiO_2 content of conventional and all mixes

7.2 Chemical analysis of mixtures

Four sets of pastes were studied and chemical analysis was determined using XRF method, the results are shown in Table 7.2.

Table 7.2: Chemical analysis of the materials, carried out using XRF method

Sample oxides	OPC50/ ROSA50	OPC20/ GGBS30/ BOS50	OPC60/ BOS35/ PG5	OPC52/ ROSA30/ BOS18	OPC80/ ROSA17/ PG3
SiO_2	24.10	23.66	16.39	20.91	20.81
TiO_2	0.56	0.50	0.38	0.50	0.47
Al_2O_3	8.77	7.13	3.76	6.59	6.50
Fe_2O_3	4.39	6.32	5.81	5.46	3.46
MnO	0.06	1.00	0.57	0.35	0.05
MgO	1.93	5.08	2.00	2.09	1.47
CaO	44.92	45.27	54.73	49.07	51.15
Na_2O	0.21	0.22	0.16	0.19	0.19
K_2O	0.65	0.40	0.43	0.57	0.60
P_2O_5	0.32	0.32	0.29	0.33	0.22
SO_3	1.74	1.35	4.15	2.16	3.62
Lol	11.91	8.49	10.40	11.41	10.30
Total	99.57	99.75	99.06	99.62	98.85
SiO_2+Al_2O_3+CaO	77.79	76.06	74.88	76.57	78.46
CaO/SiO_2	1.86	1.91	3.34	2.35	2.46
Total alkalinity (Na_2O + K_2O)	0.86	0.62	0.59	0.76	0.79
CaO/Al_2O_3	5.12	6.35	14.56	7.45	7.87
Portlandite (Lin-counts)	3200	2300	4000	3200	4000
Sample oxides	OPC60/ BOS40	OPC70/ GGBS25/ PG5	OPC50/ ROSA40/ BPD10	OPC50/ GGBS45/ BPD5	OPC40 /BOS55/ BPD5
SiO_2	15.54	20.34	22.06	20.27	14.70
TiO_2	0.42	0.41	0.50	0.39	0.41
Al_2O_3	3.42	5.39	7.91	5.55	3.25
Fe_2O_3	10.36	2.20	4.00	1.97	11.20
MnO	1.29	0.12	0.06	0.15	1.44
MgO	3.37	1.99	1.73	2.30	3.69
CaO	50.65	55.24	44.77	52.84	48.76
Na_2O	0.13	0.20	0.27	0.24	0.16
K_2O	0.32	0.54	1.29	0.90	0.44
P_2O_5	0.53	0.10	0.29	0.08	0.57
SO_3	1.67	4.60	2.21	2.47	1.43
Lol	11.56	8.49	13.74	12.05	13.24
Total	99.27	99.62	98.82	99.20	99.28
SiO_2+Al_2O_3+CaO	69.61	80.97	74.74	78.66	66.71
CaO/SiO_2	3.26	2.72	2.03	2.61	3.31
Total alkalinity (Na_2O + K_2O)	0.45	0.74	1.56	1.14	0.6
CaO/Al_2O_3	14.81	10.25	5.66	9.52	15.00
Portlandite (Lin-counts)	3800	3700	3000	3300	4000

Table 7.2 shows that for almost mixes the silica content remained at 20%. On the other hand, as the presence of alkali in the pore solution causes dissolution of silica and is considered as one of the main contributors to strength development, it can be stated that the higher the amount of alkalis in the mix, the higher the strength. It should be noted that there is an optimum alkali content in the cementitious mix above which the form and shape of the crystals, such as ettringite changes, reduce the dissolution rate of silica from slag. This will result in lower compressive and split tensile strength.

Ettringite forms hexagonal-prismatic crystals based on columns of cations of the composition $\{Ca_3[Al(OH)_6].12H_2O\}^{3+}$ in which the $Al(OH)_6{}^{3-}$ octahedra are bound up with the edge-sharing CaO_8 polyhedra. This means that each aluminium ion, bound into the crystal, is connected to Ca_2+ ions with which they share OH– ions. The intervening channels contain the SO_4^{2-} tetrahedra and remaining water molecules. The water molecules are partly bound very close into the ettringite structure (Taylor, 1997).

Nevertheless the higher alkalinity of the pore solution facilitates the dissolution of silica from the slag resulting in formation of higher amount of cementitious gel. Table 7.2 shows that the total alkalinity i.e. (Na_2O + K_2O) in OPC50/GGBS45/BPD5 is 1.14%. This suggests that more silica from slag dissolves in the pore solution to form more cementitious gel.

On the other hand, the total silica (SiO_2), aluminium oxide (Al_2O_3) and Calcium oxide (CaO) content in the mix OPC50/GGBS45/BPD5 was 78.66%. In comparison to the other mixes tested this mix had the highest percentage. This suggests that the combination of silica and calcium oxide contributed to the formation of CSH gel and increased the long term compressive and split tensile strength of the paste specimen.

The C-S-H phase in cement paste is amorphous or semicrystalline calcium silicate hydrate and the hyphens denote that the gel does not necessarily consist of 1:1 molar CaO: SiO2. The C-S-H of cement pastes gives powder patterns very similar to that of C3S pastes. The composition of C-S-H (in terms of C/S ratio) is variable depending on the time of hydration. At day one, the C/S ratio is about 2.0 and becomes 1.4–1.6 after several years (Ramachandran, 2001), furthermore when the aqueous solution has a high silica concentration, but low calcium, the C-S-H formed in the solution is expected to have a low C/S ratio (Gartner and Jennings, 1987).

Moreover, the nanostructure of C–S–H is defined by its variations, and a comprehensive understanding requires an explanation of how variations of the Ca/Si ratio, the silicate structure, and the contents of Si–OH and Ca–OH are correlated (Jeffrey et al,. 2004). According to studies by Puertas et al. (2004), through microstructural analysis confirmed that aluminium is incorporated into the silicate chains of C–S–H formed and its Ca/Si ratio appears to be limited to about 1.1, which is low compared to that of Portland cement C–S–H.

Alternatively, the content of sulphate in mix OPC50/GGBS45/BPD5 calculated as SO_3 was 2.47% suggesting that the improved strength may be as a result of activation of GGBS by sulphate. In addition, the ratio of CaO to Al_2O_3 in the same mix was the highest in comparison with the other mixes tested and was 9.52; which is close to the same ratio of Portland cement, as shown in Table 7.2. Although the amount of portlandite in mix OPC50/GGBS45/BPD5 is the highest compared to the other mixes containing 50% OPC, it can postulated that part of all the portlandite from BPD reacted with GGBS to form CSH. This may be a reason for higher strength of this mix.

The results of the XRD test showed the presence of the minerals affected the split tensile and compressive strength. The XRD diffractograms of the powder of paste samples are presented in Figure 7.2 and Table 7.3 (Also Figures in appendix from 10.21 to 10.30). XRD analysis was carried out on samples at 28 days.

The cementitious gel contributing to strength was not in a crystalline form and therefore could not be detected by XRD. It can be seen for all mixes that there were relatively large intensity peaks for portlandite, even in mixes with replacement of 50% OPC. The mix with 80% cement replacement materials showed a reduction in portlandite and intensity of Portlandite was measured about 57% which was the lowest intensity measured in comparison with rest of mixes. This confirms that a combination of GGBS/BOS was able to react with Portlandite effectively to form cementitious gel. This contributed to increase in strength. Furthermore, the mix with 80% OPC had the highest portlandite content 100% in comparison to the rest mixes indicating the higher OPC content, the higher Portlandite. The higher strength of mix OPC50-GGBS45-BPD5 with 50% cement replacement materials comparing to mix OPC20-GGBS30-BOS50 appears to be due to higher intensity of Ettringite phase in the mix. This contributed the early strength of paste mix.

Table 7.3 shows the phases of all mixes tested by XRD.

Table 7.3: Shows the phases as percentage of the highest intensity

Phases	Mixes				
	OPC50-ROSA50	**OPC20-GGBS30-BOS50**	**OPC60-BOS35-PG5**	**OPC52-ROSA30-BOS18**	**OPC80-ROSA17-PG3**
Portlandite phase	80.0	57.5	100	80.0	100
Ettringite phase	77.0	49.0	94.0	94.0	100
Hatrurite phase	96.0	100	100	100	100
Larnite phase	100	100	100	100	100
Brownmillerite phase	100	100	100	100	100
Calcium Aluminium Oxide phase	94.0	-	94.0	94.0	94.0
Quartz Low phase	96.0	100	32.0	32.0	50.0
Gypsum phase	100	71.0	86.0	71.0	71.0
Hydrocalumite phase	-	-	-	-	-
Periclase Phase	-	-	-	-	-
Phases	**Mixes**				
	OPC60-BOS40	**OPC70-GGBS25-PG5**	**OPC50-ROSA40-BPD10**	**OPC50-GGBS45-BPD5**	**OPC40-BOS55-BPD5**
Portlandite phase	100	98.0	75.0	83.0	100
Ettringite phase	80.0	89.0	77.0	77.0	71.0
Hatrurite phase	100	100	96.0	60.0	100
Larnite phase	100	100	100	100	100
Brownmillerite phase	100	100	100	100	100
Calcium Aluminium Oxide phase	-	88.0	94.0	100	-
Quartz Low phase	32.0	18.0	50.0	32.0	27.0
Gypsum phase	71.0	71.0	-	-	-
Hydrocalumite phase	-	-	100	100	100
Periclase Phase	100	-	-	-	37.0

The results of the XRD test of all mixes are shown in Figure 7.2.

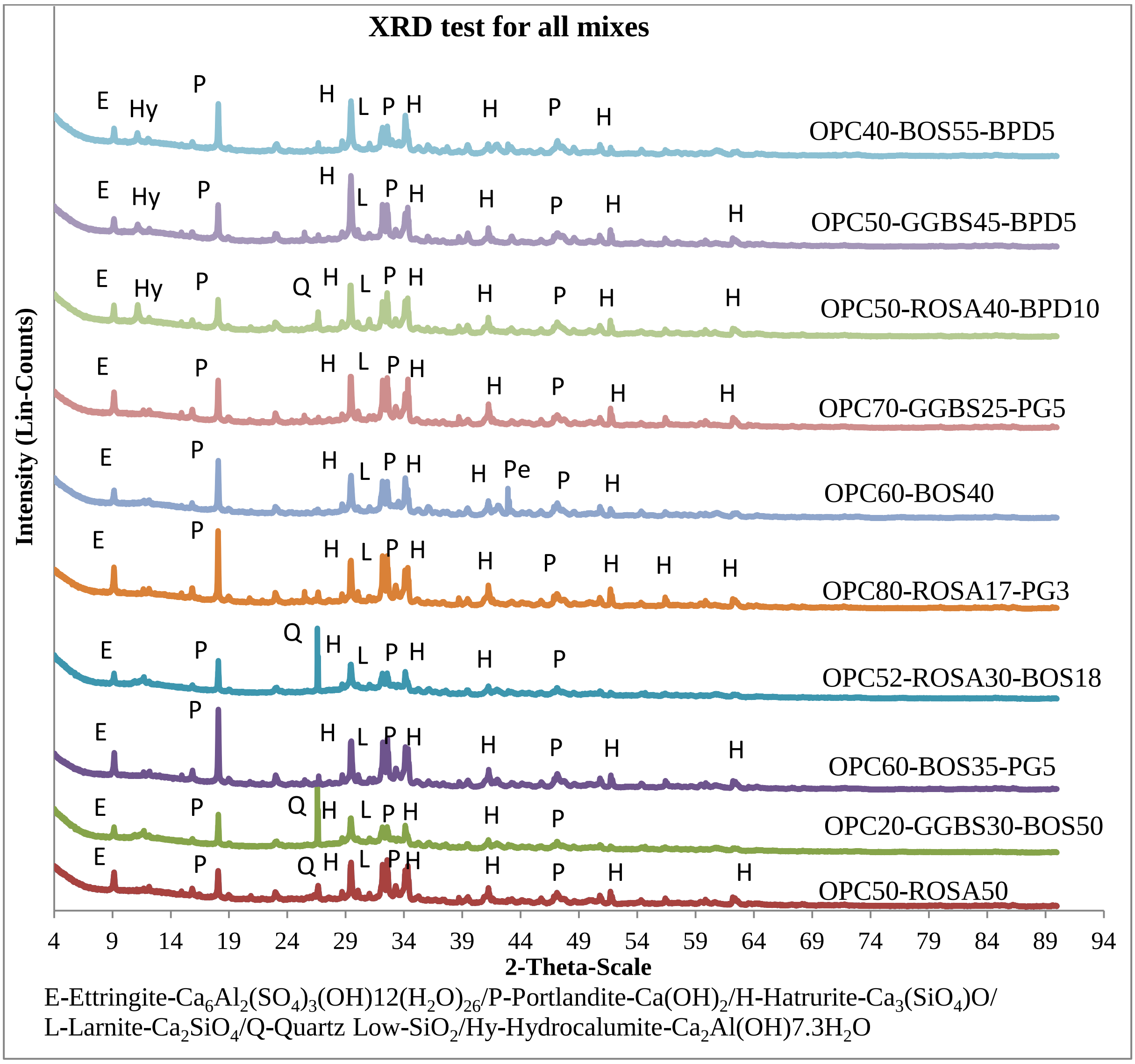


Figure 7.2: Shows the XRD results of all mixes at 28 days

8. Concrete paving blocks

8.1 Factory mix design for concrete paving blocks

The mix design obtained from a paving block manufacturer was used to make the control mix and is given in Table 8.1.

Table 8.1: Two mix designs of paving blocks used by a factory (percentage by weight)

Factory control mix I	Cement	GGBS	4mm-Dust	6mm	sand
	10%	4%	53%	9%	24%
Factory control mix II	Cement	PFA	4mm-Dust	6mm	sand
	10%	4%	53%	9%	24%

The materials used by the factory were also acquired and used in the laboratory so a mix design can be replicated from the factory and the results can be compared. The results of split tensile strength for the two different factory designed mixes cast and tested in the laboratory are given in Figures 8.3 and 8.4.

A compaction loading pressure of 400 KN was used in the laboratory for these concrete paving block mixes. The results indicate that at 28 days a split tensile strength of 3.2 and 2.6 MPa respectively was attained for their GGBS and PFA concrete paving blocks, these mixes contain the traditional 10% cement by weight. It is remarkable to see that the factory blocks of GGBS mix that were brought to the laboratory also gave an average split tensile strength of 3.2 MPa. This implies that our laboratory compaction pressure of 400 KN for the concrete blocks is an exact match with the factory's compaction. It is noteworthy to add that the paving blocks must have a minimum split tensile strength of 3.6 MPa, as specified by the BS EN1338: 2003 standard (British Standard Institute, 2003).

The mix designs for concrete paving blocks made are provided in tables 8.2 and 8.5. The constant ratio of paste to aggregates was 1:16.1 by weight. Moreover, for all mixes, approximately 80 - 95 litres of water were added to a one cubic meter mix.

8.2 Mix design for concrete paving blocks (second phase)

The second phase of this study was to select the best mix between seven mixes from the first phase. Specimens in the second phase were made incorporating three different stones with maximum particle size of 4mm, 6mm and sand. The aggregates used were obtained from the paving blocks factory. The mix design used was the factory mix design as presented in Table 8.2.

Table 8.2: Mix proportions using virgin aggregates given as percentage by weight-second phase

Mix code	OPC (%)	GGBS (%)	PFA (%)	BPD (%)	BOS (%)	ROSA (%)	PG (%)	4mm-Dust (%)	6mm (%)	Sand (%)
Factory control mix I OPC10-GGBS4	10	4.0	-	-	-	-	-	53	9	24
Factory control mix II OPC10-PFA4	10	-	4.0	-	-	-	-	53	9	24
OPC2.8-GGBS4.2-BOS7.0	2.8	4.2	-	-	7.0	-	-	53	9	24
OPC8.4-BOS4.9-PG0.7	8.4	-	-	-	4.9	-	0.7	53	9	24
OPC7.3-ROSA4.2-BOS2.5	7.3	-	-	-	2.5	4.2	-	53	9	24
OPC5.6-BOS7.7-BPD0.7	5.6	-	-	0.7	7.7	-	-	53	9	24
OPC8.4-BOS5.6	8.4	-	-	-	5.6	-	-	53	9	24
OPC7.0-ROSA7.0	7.0	-	-	-	-	7.0	-	53	9	24
OPC7.0-GGBS6.3-BPD0.7	7.0	6.3	-	0.7	-	-	-	53	9	24

8.3 Results and discussion for concrete paving blocks (second phase)

Figures 8.1 to 8.4 showed the results of the tests that were carried out to determine the compressive strength and split tensile strength.

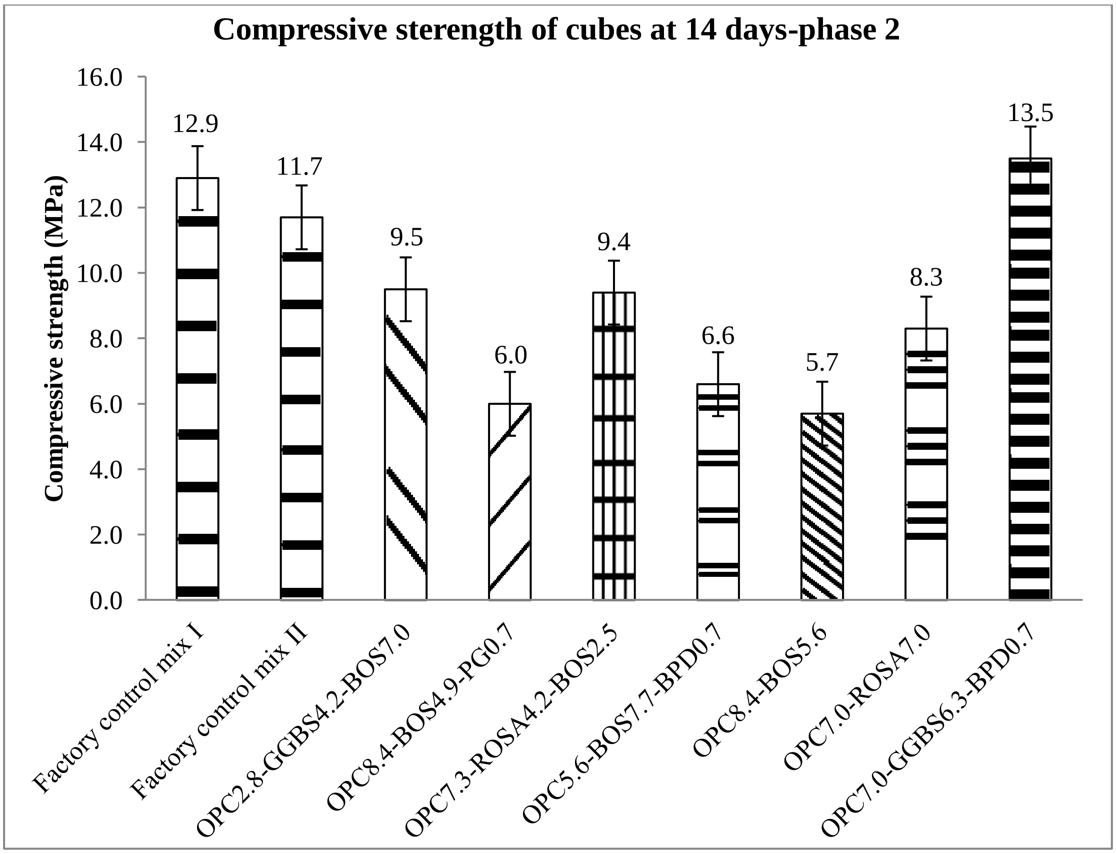


Figure 8.1: Compressive strength of 50x50mm cubes at 14 days

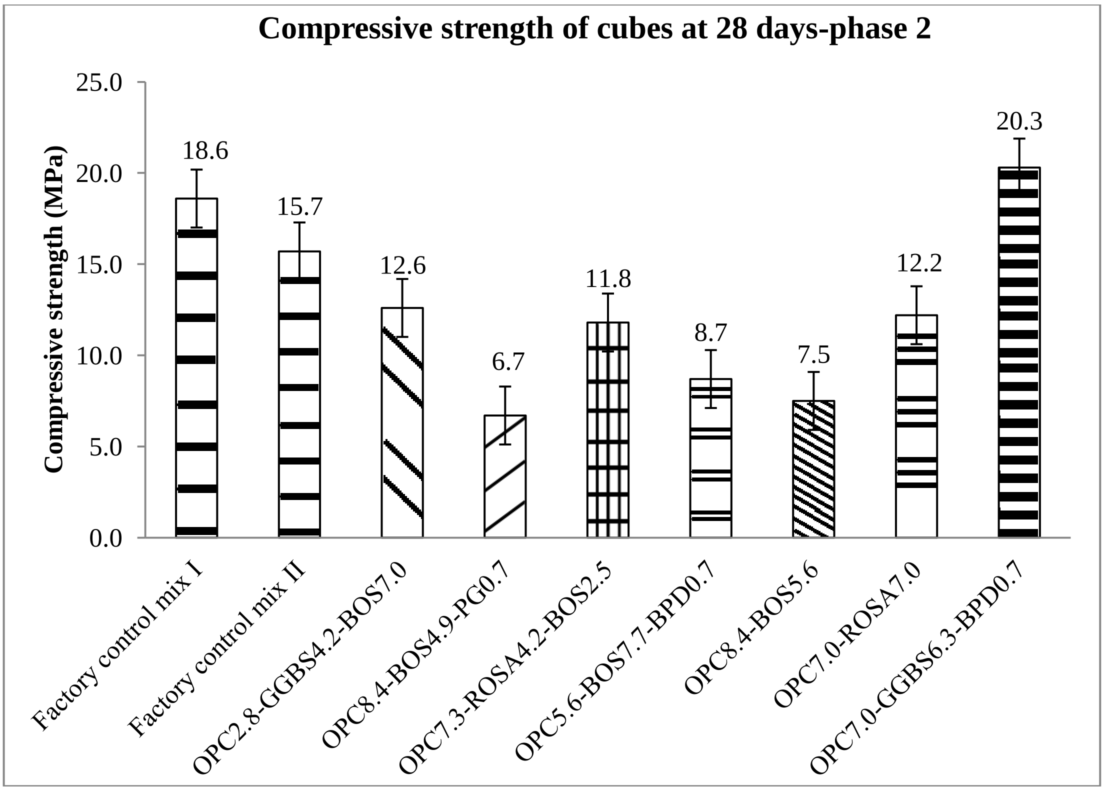


Figure 8.2: Compressive strength of 50x50mm cubes at 28 days

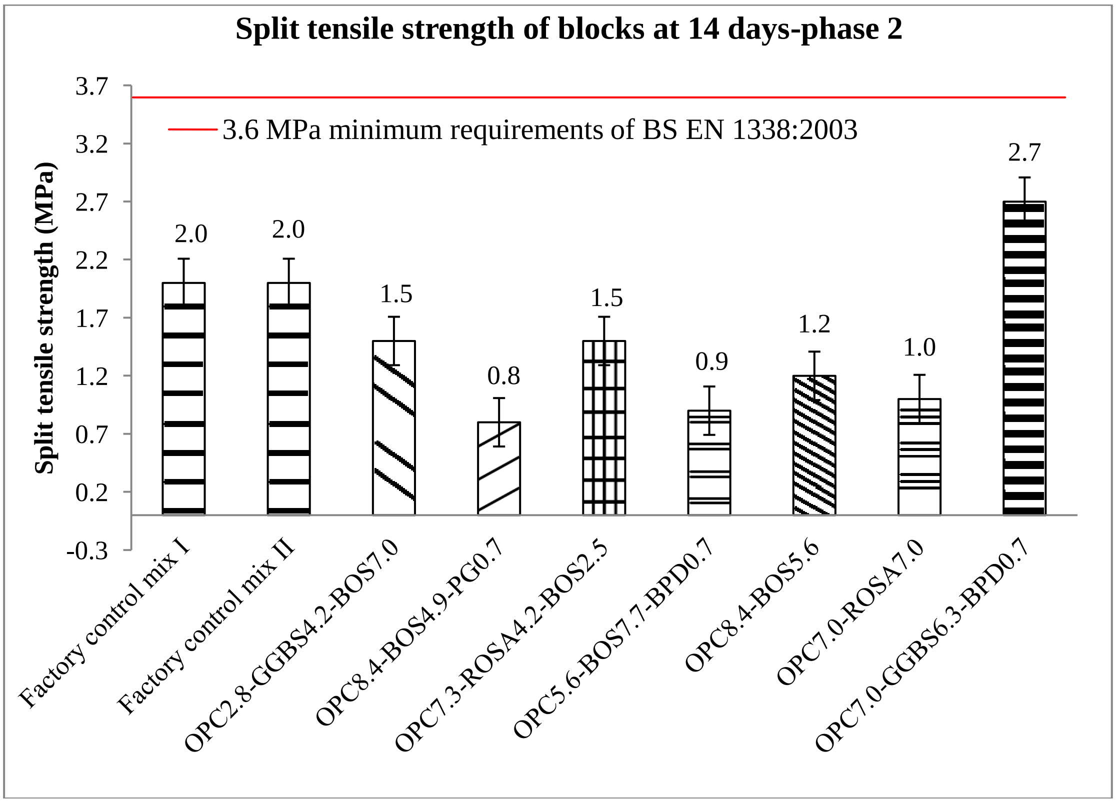


Figure 8.3: Split tensile strength of blocks at 14 days

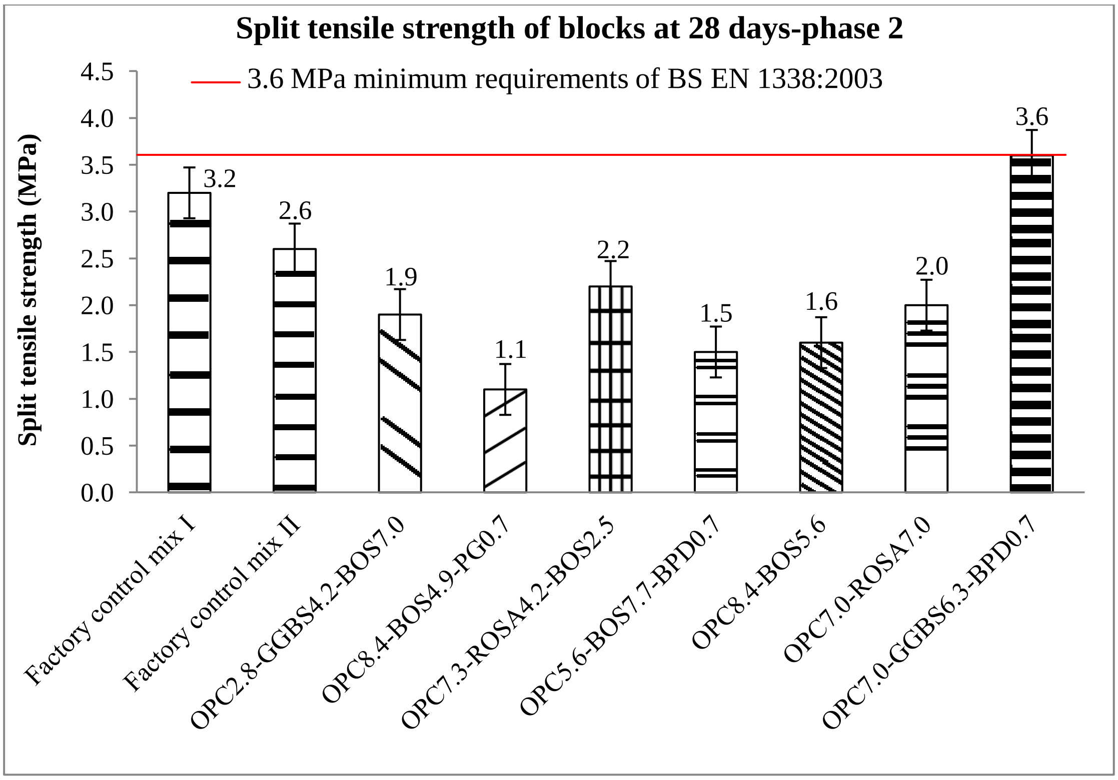


Figure 8.4: Split tensile strength of blocks at 28 days

As expected the compressive strength of the cubes showed the same trend as concrete paving blocks. It can be seen that the maximum compressive strength and split tensile strength can be achieved by using 7.0% OPC, 6.3% GGBS and 0.7% BPD. The compressive and split tensile strength at 28 days was 20.3MPa and 3.6MPa respectively. The result of split tensile strength presented in Figure 8.4 showed only mix OPC7.0-GGBS6.3-BPD0.7 was 3.6MPa at 28 days which is the limit of the British standard of BS EN1338: 2003 (British Standard Institute, 2003).

The average ratio of compressive strength to split tensile strength in the second phase was 5.7.

On the other hand, the factory control mixes and all other laboratory mixes containing OPC-GGBS-BOS, OPC-BOS-PG, OPC-BOS-ROSA, OPC-BOS-BPD, OPC-BOS and OPC-ROSA did not satisfy the 3.6 MPa minimum requirements of BS EN1338: 2003 (British Standard Institute, 2003).

As it is well established, the ground granulated blast furnace slag (GGBS) is a pozzolanic material which can be used as a cementitious ingredient in either cement or concrete composites. The use of GGBS is well established in many cement applications where it provides enhanced durability, including high resistance to chloride penetration, resistance to sulphate attack and protection against alkali silica reaction (Wild et al., 1995). The hydration mechanism of a combination of GGBS and Portland cement is slightly more complex than that of Portland cement. The reaction involves the activation of GGBS by alkalis and sulphate to form its own hydration products. Some of these combine with Portland cement products to form further hydrates that have a pore blocking effect. Furthermore, BPD in this mix provides a source of alkalinity, which acts as an alkaline and will improve the GGBS hydration with OPC further.

8.4 Durability tests in the second phase

Table 8.3 shows the results of the density, slip/skid resistance, weathering resistance (water absorption and freeze/thaw) in the second phase. The results of the slip/skid resistance show that all paving block mixes made in the laboratory have excellent skid resistant surfaces and the potential for slipping is extremely low according to the BS EN1338: 2003 (British Standard Institute, 2003) definition, as given in Table 8.4. The densities of all mixes in first phase are given in Table 8.3. The density as expected the ranges between 2380 to 2460 kg/m^3.

Table 8.3: Density, slip/skid resistance and weathering resistance results of concrete paving blocks

Mix code	Density (Kg/m^3)	Slip/Skid resistance (BPN)	Weathering Resistance	
			Water Absorption (%)	Freeze/thaw Resistance (Kg/m^2)
OPC10/GGBS4 (Factory control mix I)	2383	100	5.4	All blocks < 1.0
OPC10/PFA4 (Factory control mix II)	2396	92	5.8	
OPC2.8/GGBS4.2/BOS7.0	2395	102	4.7	
OPC7.3/ROSA4.2/BOS2.5	2381	103	5.9	
OPC8.4/BOS4.9/PG0.7	2458	103	5.8	
OPC5.6/BOS7.7/BPD0.7	2438	102	5.5	
OPC8.4/BOS5.6	2451	103	5.7	
OPC7.0/ROSA7.0	2449	102	6.2	
OPC7.0/GGBS6.3/BPD0.7	2405	94	5.6	

The following slip resistance table obtained from the British standard BS EN1338: 2003 (British Standard Institute, 2003), gives an indication of the values against the potential to slip.

Table 8.4: Pendulum test values and definition given by BS EN1338: 2003

British Pendulum Number test value (BPN)	Potential for slip
Below 19	High
20 to 39	Moderate
40 to 74	Low
Above 75	Extremely low

In addition, the result of the freeze/thaw resistance test shows that all mixes in Table 8.4 meet the British standard of BS EN1338: 2003 (British Standard Institute, 2003).

On the other hand, according to the standard the results from the water absorption test should be less than 6%, therefore, from the results presented in Table 8.3 it can be seen that only the OPC-ROSA mix did not satisfy the minimum requirements for the water absorption test as the result was 6.2% which is higher than the 6.0% limit set. However, the other mixtures met the minimum requirements and gave satisfactory results, the results ranged from 4.7% to 5.9%.

8.5 Conclusion in the second phase:

The results presented in Figure 8.4 and Table 8.4 showed that mix OPC7.0-GGBS6.3-BPD0.7 (OPC50-GGBS45-BPD5) was the best mix in the second phase as it satisfied all minimum requirements for split tensile strength and durability tests at 28 days, in accordance to BS EN1338 (British Standard Institute, 2003). The above mix was then used in the third phase, as outlined in section 8.4.

Furthermore, the effect of inclusion of aggregates in the mixes at the second phase resulted in an average of 70% and 63.3% reduction in compressive and split tensile strengths, respectively, in comparison to results obtained in the first phase for mixes without aggregates. The reduction in strength is due to the effect of moist (Condition tested in phase 1) and saturated specimens (As BS EN standard requires for paving blocks, the blocks were submerged 24 hour before testing) sand also relatively poor bonds between cementitious paste and aggregates, also, inferior quality aggregates used as breaking zones showed failure through the broken stones (see Figure10.14 in the appendix).

8.6 Mix design for concrete paving blocks (third phase)

The third phase of this study was to use the best mix OPC7.0-GGBS6.3-BPD0.7 (OPC50-GGBS45-BPD5) from the second phase and complete replacement of 4mm and 6mm natural aggregates with waste recycled materials such as IBAA, RCA, RCG and RB with the same grading as 4mm and 6mm aggregates obtained from the factory as shown in Table 8.5. Concrete paving blocks were tested for split tensile strength and compressive strength at 14 and 28 days, slip/skid resistance, weathering resistance and density.

Table 8.5: Selection of the best mix and replacing coarse aggregates with different recycled materials given as percentage by weight-third phase

Mix No.	OPC (%)	GGBS (%)	BPD (%)	BOS (%)	4mm-Dust (%)	6mm (%)	Sand (%)	Steel Fibre (%)	PVA (Kg/m^3)
Best mix (OPC7/GGBS6.3/BPD0.7)	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 6 & 4mm IBAA replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 4mm IBAA replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 6 mm IBAA replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 6 mm RCA type I replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 6 mm RCA type II replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 4 mm RCG replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 6 mm RB replacement	7.0	6.3	0.7	-	53	9	24	-	-
Best mix with 1.5 % steel fibre	7.0	6.3	0.7	-	53	9	24	1.5	-
Best mix with 6 PVA	7.0	6.3	0.7	-	53	9	24	-	6
Best mix with 10 PVA	7.0	6.3	0.7	-	53	9	24	-	10

8.7 Results and discussion for concrete paving blocks (third phase)

In the third phase of this study, the best mix from the seven mixes in the second phase was selected. The best mix was OPC7.0-GGBS6.3-BPD0.7 (OPC50-GGBS45-BPD5) as it showed the highest compressive strength and split tensile strength also showed satisfactory results for all the other durability tests that complied with the British standards. This mix was then used with seven different recycle natural coarse aggregates such as IBAA, RCA, RB and RCG. Aggregate sizes of 4mm and 6mm were used with same grading as factory aggregates. Furthermore, for the last two mixes 1.5% steel fibre and PVA (6 and 10 kg/m^3) was also used with the same mix, as shown in Table 8.5.

Figures 8.5 to 8.8 show the results of the tests carried out to determine the compressive strength and split tensile strength. The maximum compressive strength achieved by using 6kg/m^3 PVA with the best mix and the strength at 28 days was 19.1 MPa, also the result of split tensile strength was 2.0 MPa at 28 days and did meet the minimum requirements of split tensile strength according to BS EN1338: 2003. It was observed that strength of mix containing steel fibre was slightly less than same mix with PVA fibre suggesting that the effect of fibre on compressive strength was not significant. However the split tensile strength was found to be affected significantly by the type of fibre. Using 1.5% steel fibre with the best mix improved the split tensile strength at early age and the highest split tensile strength was 3.2 MPa at 14 days and 3.6 MPa at 28 days.

It can be seen from the Figure 8.8 that only best mix with and without steel fibre at 28 days achieved the minimum requirements of split tensile strength according to BS

EN1338: 2003, whilst the other mixes in the same phase containing IBAA, RCA, RCG and RB as replacement of natural coarse aggregates and added PVA did not satisfy the minimum requirements according to BS EN1338: 2003 (British Standard Institute, 2003).

The average ratio of compressive strength to split tensile strength in the third phase was 5.9.

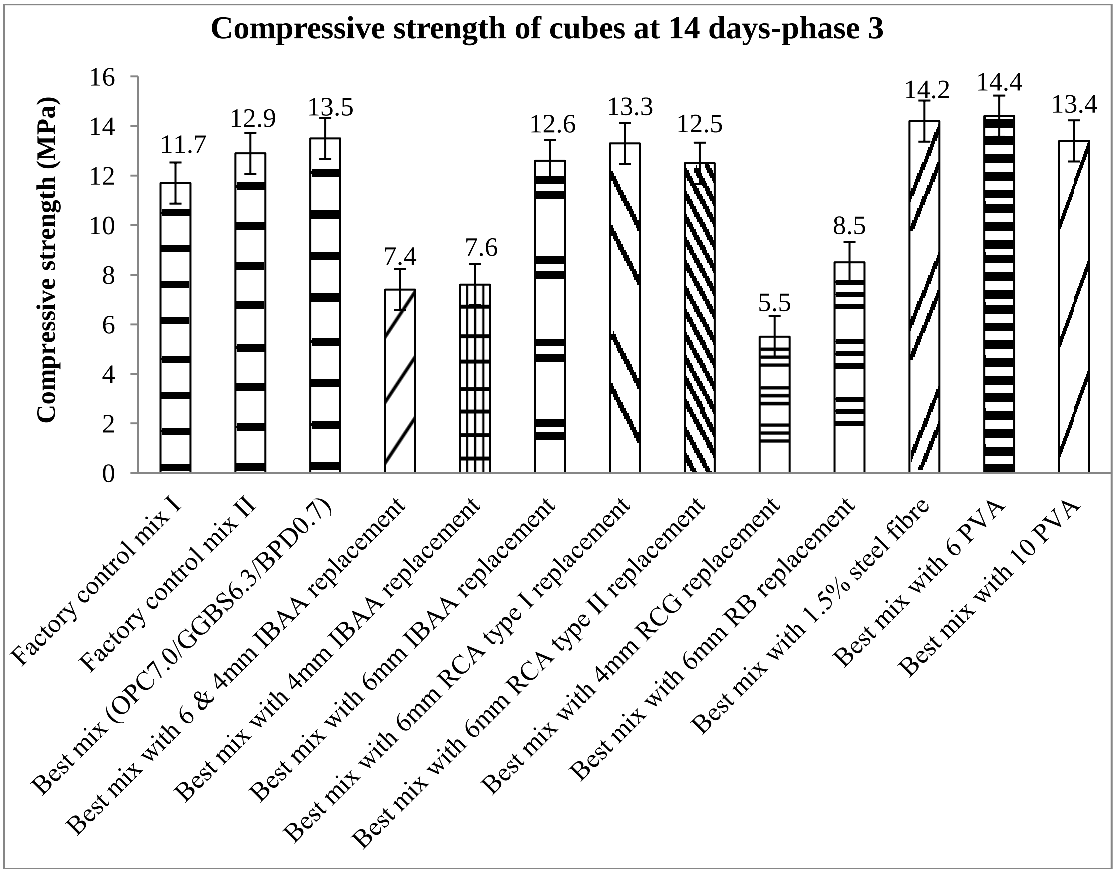


Figure 8.5: Compressive strength of 50x50mm cubes at 14 days

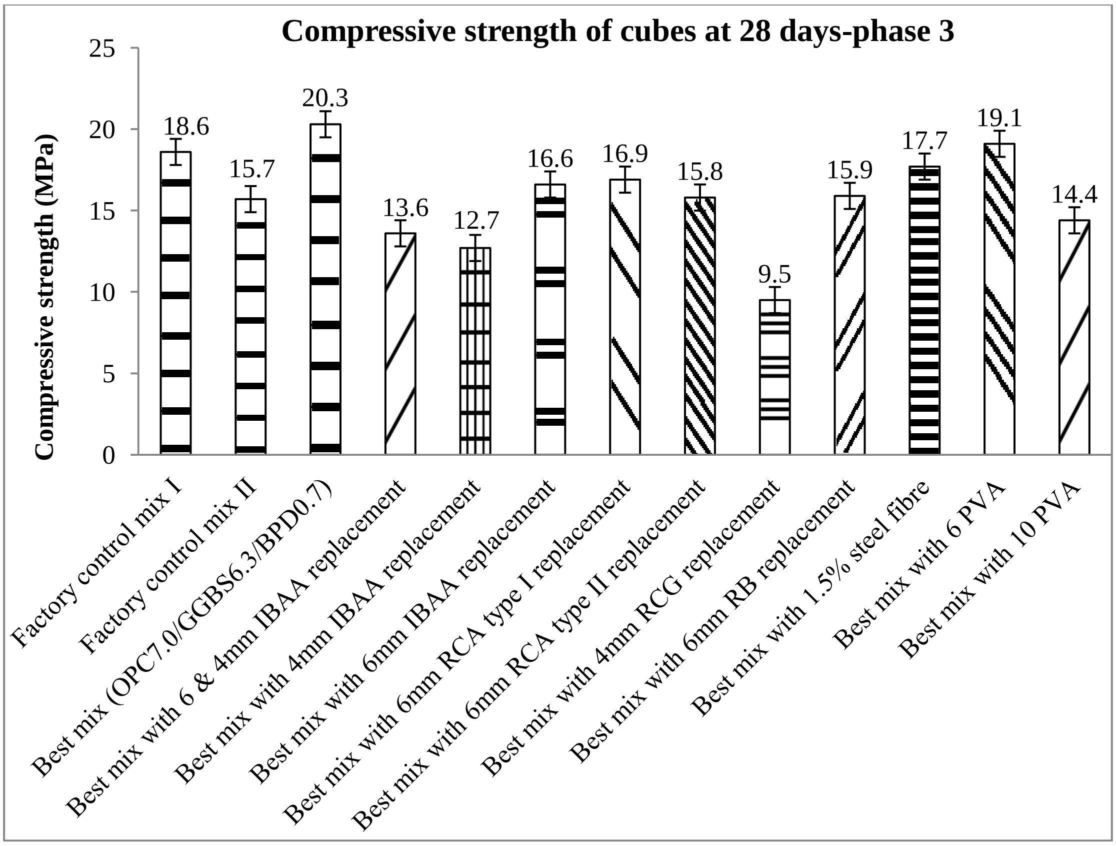


Figure 8.6: Compressive strength of 50x50mm cubes at 28 days

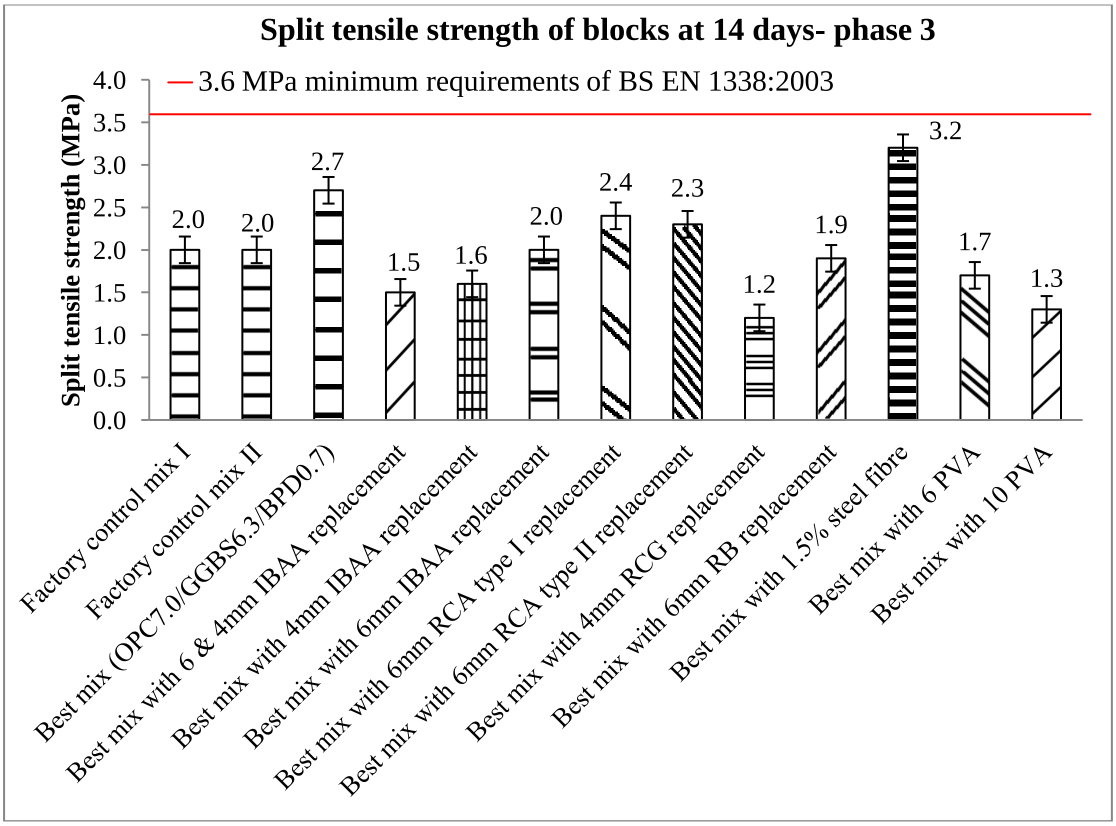


Figure 8.7: Split tensile strength of blocks at 14 days

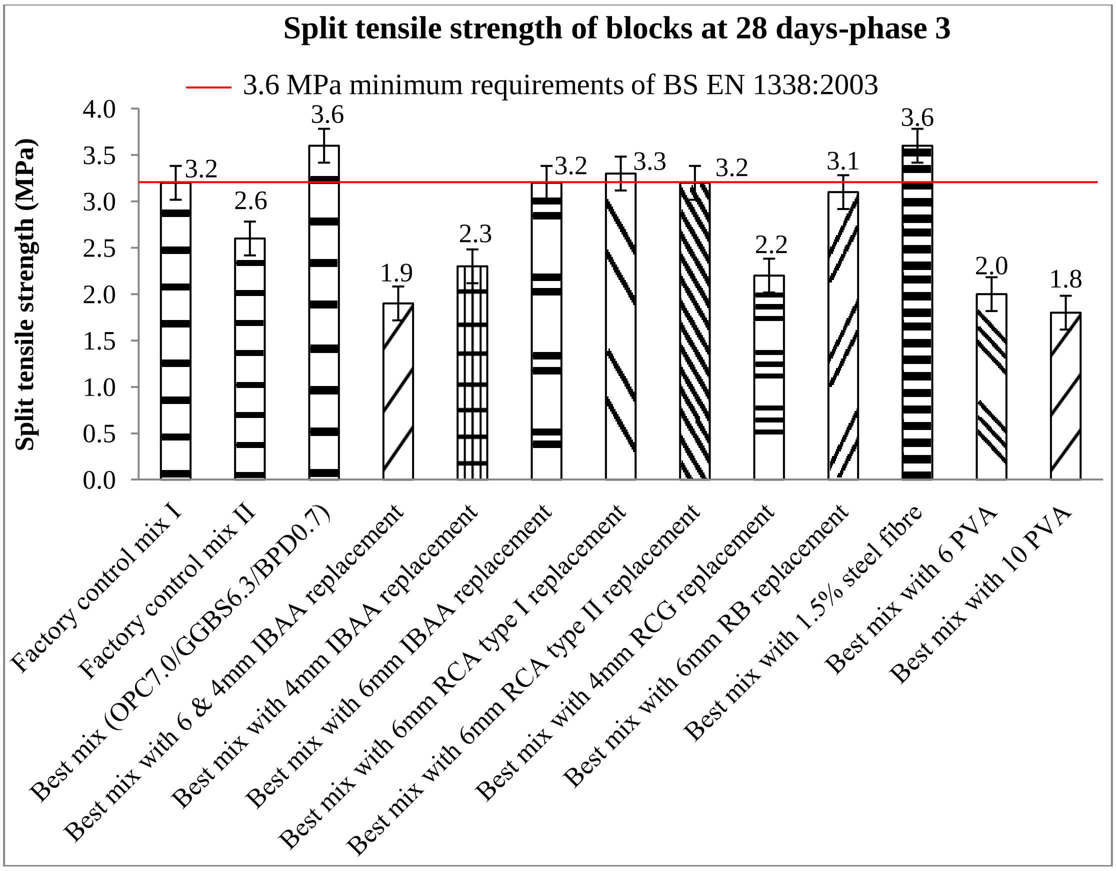


Figure 8.8: Split tensile strength of blocks at 28 days

8.8 Durability tests in third phase

Table 8.6 shows the results of the density, slip/skid resistance, weathering resistance (water absorption and freeze/thaw) in the third phase.

The results of the slip/skid resistance test shows that all concrete paving block mixes made in the laboratory have an excellent skid resistant surface and the potential for slip is extremely low according to the BS EN1338: 2003 (British Standard Institute, 2003) definition, as given in Table 8.3. In addition, the results of the freeze/thaw resistance test shows that all mixes, except mixes with IBAA 6 and 4mm replacement, met the British standards of BS EN1338: 2003 (British Standard Institute, 2003).

However, the water absorption test should show a result of less than 6% according to the BS EN1338: 2003 standard (British Standard Institute, 2003). Table 8.6 presents the results for the water absorption test, from the table it can be seen that only mixes with IBAA 6mm, RCA I&II 6mm, RB 6mm aggregate replacement and mixes with 1.5% SF met the minimum requirements for the water absorption test, whilst, the results of mixes with IBAA 6 and 4mm, IBAA 4mm, RCG 6mm aggregate replacement, and mixes with 6 and 10 (Kg/m^3) PVA-Fiber did not satisfy the minimum requirements for the water absorption. The higher water absorption in mix containing PVA fibre may be due to balling effect and therefore large pores and voids exist around the fibres. Furthermore the mix made with RCG appears to have higher porosity due to shape and size of crushed glass aggregates, thus higher water absorption was observed. The mixes containing IBBA showed poor performance in terms of water absorption and freeze/thaw resistance. This appears to be due to significant contamination of IBBA with various waste materials such as steel, glass, rubber, etc.

The results for the mixes that did not satisfy the minimum requirements varied from 7.5% to 10.9% which is substantially higher than the 6.0% limit set.

Table 8.6: Density, slip/skid resistance and weathering resistance results of concrete paving blocks

Mix	Density (Kg/m^3)	Slip/Skid resistance (BPN)	Weathering Resistance	
			Water Absorption (%)	Freeze/thaw Resistance (Kg/m^2)
OPC10/GGBS4 (Factory control mix I)	2383	100	5.4	< 1.0
OPC10/PFA4 (Factory control mix II)	2396	92	5.8	
OPC7.0/GGBS6.3/BPD0.7 (Best mix)	2405	94	5.6	
Best mix with 6 mm IBAA replacement	2385	97	5.6	
Best mix with 6 mm RCA type I replacement	2385	101	5.9	
Best mix with 6 mm RCA type II replacement	2393	98	5.8	
Best mix with 6 mm RCG replacement	2284	105	7.5	
Best mix with 6 mm RB replacement	2409	98	6.0	
Best mix with 1.5 % steel fibre	2437	85	6.0	
Best mix with 6 PVA	2374	107	7.5	
Best mix with 10 PVA	2382	107	8.1	
Best mix with 6 & 4mm IBAA replacement	2258	76	10.9	1.5
Best mix with 4mm IBAA replacement	2317	82	10.6	1.2

9. Conclusions and recommendations for future work

The potential application of this research is to reduce the amount of Portland cement content in manufacturing of paving blocks and thereby reducing the carbon footprint of the construction industry. Such a goal is desirable from the point of view of combating global warming.

This research study provides a further environmental benefit by re-using industrial/mineral waste materials. This will lead to a reduction in the stockpile of such waste materials, thus decreasing their impact on the environment and easing the problems associated with the disposal of waste materials to landfill.

Economic benefits should also be felt by industry due to the reduced waste disposal costs and freedom from complex laws and regulations relating to the disposal of waste material. Concrete producers will also benefit from lower production costs due to the ready availability and low cost of industrial waste.

The following conclusions can be drawn from this research:

1. This study showed that compressed binder paving blocks could be successfully prepared using cement and by-product minerals such as basic oxygen slag (BOS), ground granulated blast furnace slag (GGBS), run-of-station ash (ROSA), plasterboard gypsum (PG), and cement by pass dust (BPD) in production of paving blocks to achieve the required strength for paving blocks.

2. The materials, such as; ROSA, BOS and GGBS were more effective in reducing the amount of cement content than PG and BPD.
3. Up to 80 percent replacement of Portland cement can be achieved in binders and this can lead to reduced cement contents for production of binder paving blocks in accordance to the BS EN 1338:2003.

4. Results of all group mixes in binder paving blocks showed that BOS up to 70%, ROSA up to 60%, GGBS up to 45%, BPD up to 20%, and PG up to 5% by weight can replace the Portland cement without negative impacts on their desirable properties in accordance to the BS EN 1338: 2003.

5. The results of binary combinations of the waste materials and by-product materials showed that OPC-ROSA mix had the highest split tensile strength (5.4 MPa) and compressive strength compare to the other combinations of OPC-BOS.

6. The results of ternary combinations of the waste materials and by-product materials showed that OPC50-GGBS45-BPD5 mix had the highest split tensile strength (5.9 MPa) compare to the other combinations groups.

7. The concrete paving blocks prepared with OPC50-GGBS45-BPD5 (OPC7.0-GGBS6.3-BPD0.7) satisfied the minimum requirements of split tensile strength (3.6 MPa). This mix can be used in the factory to reduce cement content by up to 30% comparison to the percent of cement used in factories nowadays.

8. The mixture OPC50-GGBS45-BPD5 (OPC7.0-GGBS6.3-BPD0.7) showed good results in the slip/skid resistance test, freeze/thaw test and water absorption test. This mixture performed well in the slip/skid resistance, freeze/thaw and water absorption tests.

9. The concrete paving blocks prepared with OPC-ROSA, OPC-GGBS-BOS, OPC-ROSA-BOS, OPC-GGBS-BOS, OPC-BOS-PG and OPC-BOS-BPD, did not meet the minimum requirement of 3.6 MPa, but they did perform well in durability tests. Nevertheless, these mixes would not be appropriate to be used on site as both physical/mechanical strength and weathering durability criteria should be met.

10. The concrete paving blocks prepared with OPC50-GGBS45-BPD5 (OPC7.0-GGBS6.3-BPD0.7) mix and IBAA, RCG, RB, PVA for 6 and 4mm aggregates replacement did not meet the minimum requirement of 3.6 MPa, whereas the same mix using 1.5% steel fiber and natural aggregate met the minimum requirements of the British standard with 3.6 MPa on split tensile strength.

11. The results of XRD of all selected mixes showed existence of ettringite in all ages. On the other hand the amount of portlandite in mix OPC50-GGBS45-BPD5 is the highest compared to the other mixes containing 50% OPC, it can be postulated that part of all the portlandite BPD reacted with GGBS to form CSH. This may be a reason for higher strength of this mix.

12. It can be seen for all mixes that there were relatively large intensity peaks for portlandite, and in mixes with replacement 50% OPC the portlandite was high. While the mix with 80% OPC replacement had a reduction in portlandite. Furthermore, the mix with 80% OPC had the highest portlandite content in comparison to the other mixes.

13. Response surface methods could predict the split tensile strength of pastes. However the error of RSM was small. Furthermore, the results of the method for predicting the split tensile and compressive strength were used for selecting ten groups. The models could predict the 28 day split tensile and compressive strength of the pastes using by-product materials and waste materials from the same source with the same chemical compositions.

14. The results of this research will be useful for the factories to use the best mix achieved and reduce the percent of cement used, which will benefit the environment to reduce the emission of CO_2.

Suggested further work that should be carried out for future research:

The following suggestions were indicated about possible future work from this research.

1. The mechanism of the hydration reactions of binary and ternary blends in ten different groups of mixes were tested in this research, on the other hand, it is recommended for future researchers to use scanning Electron Microscopy (SEM) to provide a more detailed morphology changed with the interactions of the chemical components. It is suggested to identify various chemical and crystalline phase within cementitious matrix to determine the reaction mechanisms between BOS, BPD and ROSA.

2. It should be investigated whether it is possible to use the best mix for other construction products such as building blocks.

3. It is suggested that for future researchers to use partial replacement of natural aggregates by using recycled concrete aggregate (RCA), recycle crushed glass (RCG), recycled bricks (RB) and incinerator bottom ash aggregate (IBAA). Also optimise aggregates grading in the mixes to achieve the highest possible strength.

4. Investigate the effect of different types of fibre materials and length, diameter and shape on split tensile strength of paving blocks.

5. Use the elevated temperature curing to investigate the improvement of the strength of paving blocks.

6. Use different sources of same materials to investigate the variation in raw material and it's consistency for this study and find its effect on strength of blocks.

7. It is recommended to investigate the strength of some mixes at longer curing age, particularly those mixes containing BOS and GGBS.

8. It is suggested to use chemical admixtures with the mixes which did not achieved the minimum required strength to improve the strength.

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10. Appendix

10.1 Some pictures related to the research

Figure 10.1: Concrete paving blocks and cubes produced in this research

Figure 10.2: Paving blocks and cubes kept in containers for curing

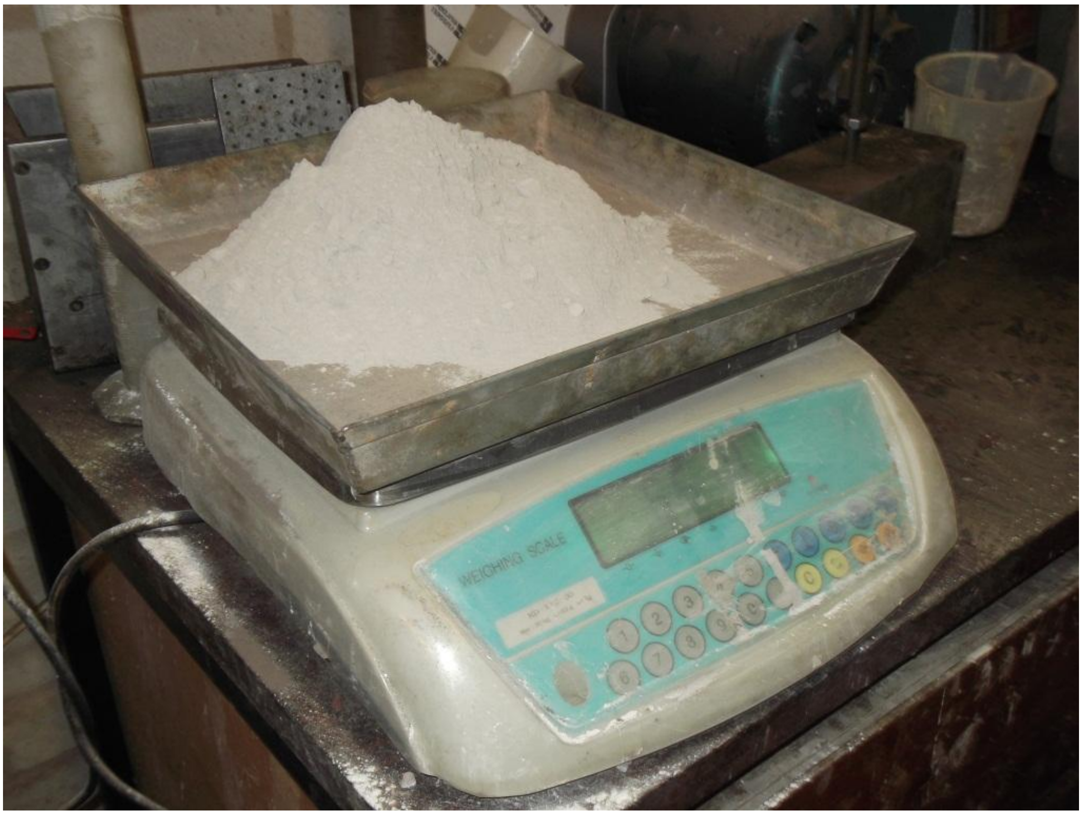

Figure 10.3: The scale used

Figure 10.4: The mixer used in making paste mixes

Figure 10.5: The mixer used in making concrete mixes

Figure 10.6: Pressing machine used

Figure 10.7: Mould compaction under the pressing machine test specimen

Figure 10.8: Compression testing machine with a maximum capacity load of 2000 kN

Figure 10.9: Paving block in steel frame for split tensile strength test

Figure 10.10: Cube for compressive strength test

Figure 10.11: Freezing chamber

Figure 10.12: Freeze-thaw resistance test specimen

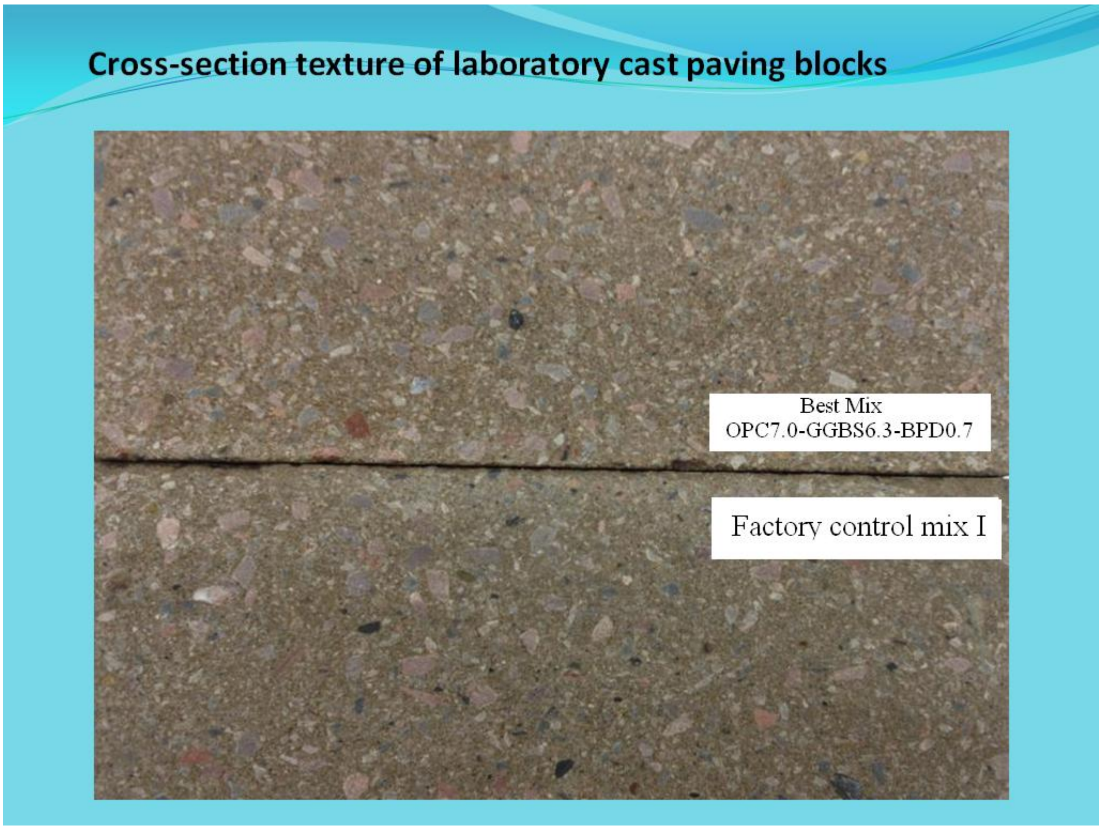

Figure 10.13: Cross-section of laboratory cast paving block between best mix and factory control mix

Figure 10.14: Cross-section of laboratory cast concrete paving block after testing

10.2 Results of all mixes as groups in the first phase

Table 10.1: The first compaction method average results i.e. rammer application to compact the materials in the mould

Mix code		Type	Age (days)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC40/GGBS30/ BOS30							
OPC	40%	Blocks	14	3.1574	41.87	2160	1.81
GGBS	30%						
BOS	30%						
W/B	0.15						

Table 10.2: The second compaction method results i.e. hammer drill compaction technique to compact the materials in the mould

Mix code		Type	Age (days)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC40/GGBS30/ BOS30							
OPC	40%	Blocks	14	2.7504	30.07	1890	1.30
GGBS	30%						
BOS	30%						
W/B	0.15						

Table 10.3: The third compaction method results i.e. hammer drill compaction technique with vibrating table

Mix code		Type	Age (days)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC40/GGBS30/ BOS30							
OPC	40%	Blocks	14	2.7604	30.99	1890	1.34
GGBS	30%						
BOS	30%						
W/B	0.15						

Table 10.4: The pressing action technique results under different pressing loads (using compression machine)

Mix code		Type	Age (days)	Pressing load (kN)	Mass (kg)	Average failure load (kN)	Average density (kg/m^3)	Average split tensile strength (MPa)
OPC40/GGBS30/ BOS30								
OPC	40%	Blocks	14	15	2.6734	53.20	1833	2.3
				20	2.7372	55.52	1877	2.4
				25	2.7304	57.83	1872	2.5
GGBS	30%			30	2.9112	64.77	1996	2.8
				40	2.9307	67.08	2010	2.9
				70	2.9752	71.71	2030	3.1
BOS	30%			100	3.1380	76.33	2009	3.3
				150	3.1745	87.89	2162	3.8
				200	3.1734	90.21	2176	3.9
W/B	0.15			250	3.2703	92.53	2242	4.0
				400	3.2615	129.54	2236	5.6

Tables from 10.5 to 10.11 show the results of strength by suing different mixtures at first year as preliminary mixes.

Table 10.5: Shows compressive and split tensile strength results for PG5-GGBS60-BOS35 after 14 days

Mix code PG5/GGBS60/BOS35		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at max. load (MPa)
PG	5%	Cubes	14	1	0.2854	36.00	2283	14.40	15.34
GGBS	60%			2	0.2764	29.81	2211	11.93	
				3	0.2756	49.25	2205	19.70	
BOS	35%	Blocks	14	1	2.6043	40.75	1790	1.80	1.82
W/B	0.15			2	2.6982	41.69	1850	1.84	

Table 10.6: Shows compressive and split tensile strength results for PG10-ROSA30-OPC60 after 14 days

Mix code PG10/ROSA30/OPC60		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average stress at max. load (MPa)
PG	10%	Cubes	14	1	0.2486	69.00	1990	27.60	34.61
ROSA	30%			2	0.2576	102.50	2060	41.00	
				3	0.2550	88.06	2040	35.22	
OPC	60%	Blocks	14	1	2.4745	27.75	1700	1.22	1.20
W/B	0.15			2	2.4386	28.94	1670	1.28	
				3	2.4245	25.25	1660	1.11	

Table 10.7: Shows split tensile strength results of blocks for BPD10-GGBS54-BOS36 after 14 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Average split tensile strength (MPa)
BPD10/GGBS54/BOS36									
BPD	10%	Blocks	14	1	2.8680	50.37	1970	2.22	2.20
GGBS	54%								
BOS	36%			2	2.9070	47.31	1990	2.09	
W/B	0.15			3	2.9160	51.62	1999	2.28	

Table 10.8: Shows split tensile strength results of blocks for PG5-GGBS60-BOS35 after 14 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Average split tensile strength (MPa)
PG5/GGBS60/BOS35									
PG	5%	Blocks	14	1	2.6043	40.75	1790	1.80	1.82
GGBS	60%								
BOS	35%			2	2.6982	41.69	1850	1.84	
W/B	0.15								

Table 10.9: Shows split tensile strength results of blocks for PG10-GGBS60-BOS30 after 14 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Average split tensile strength (MPa)
PG10/GGBS60/BOS30									
PG	10%	Blocks	14	1	2.5825	30.57	1770	1.32	1.26
GGBS	60%			2	2.5684	28.07	1760	1.21	
BOS	30%								
W/B	0.15			3	2.5704	28.69	1760	1.24	

Table 10.10: Shows split tensile strength results of blocks for PG10-ROSA30-OPC60 after14 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Average split tensile strength (MPa)
PG10/ROSA30/OPC60									
PG	10%	Blocks	14	1	2.4745	27.75	1700	1.22	1.20
ROSA	30%			2	2.4386	28.94	1670	1.28	
OPC	60%								
W/B	0.15			3	2.4245	25.25	1660	1.11	

Table 10.11: Shows split tensile strength results of blocks for PG5-ROSA35-OPC60 after 14 days

<table>
<tr><th colspan="2">Mix code</th><th rowspan="2">Type</th><th rowspan="2">Age (days)</th><th rowspan="2">No.</th><th rowspan="2">Mass (kg)</th><th rowspan="2">Failure load (kN)</th><th rowspan="2">Density (kg/m^3)</th><th rowspan="2">Split tensile strength (MPa)</th><th rowspan="2">Average split tensile strength (MPa)</th></tr>
<tr><th colspan="2">PG5/ROSA35/OPC60</th></tr>
<tr><td>PG</td><td>5%</td><td rowspan="4">Blocks</td><td rowspan="4">14</td><td>1</td><td>2.4538</td><td>30.33</td><td>1680</td><td>1.31</td><td rowspan="4">1.41</td></tr>
<tr><td>ROSA</td><td>35%</td><td rowspan="2">2</td><td rowspan="2">2.4662</td><td rowspan="2">32.78</td><td rowspan="2">1690</td><td rowspan="2">1.42</td></tr>
<tr><td>OPC</td><td>60%</td></tr>
<tr><td>W/B</td><td>0.15</td><td>3</td><td>2.4724</td><td>34.64</td><td>1690</td><td>1.49</td></tr>
</table>

10.2 Results of all mixes as groups in the first phase

Table 10.12: Mix proportion for (ROSA–OPC) paste mixtures

Mix Code	Mix	ROSA (%)	OPC (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
					14	28	14	28
ROSA30/OPC70	1	30	70	0.15	18.29	24.21	3.63	4.25
ROSA40/OPC60	2	40	60	0.15	17.18	24.94	3.61	5.22
ROSA50/OPC50	3	50	50	0.15	17.82	26.38	3.88	5.42
ROSA60/OPC40	4	60	40	0.15	15.85	23.24	2.89	3.72
ROSA70/OPC30	5	70	30	0.15	11.53	16.82	2.23	2.90

Table 10.13: Mix proportion for (OPC-GGBS–BOS) paste mixtures

Mix Code	Mix	OPC (%)	GGBS (%)	BOS (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC40/GGBS30/BOS30	1	40	30	30	0.15	17.37	23.24	3.28	4.30
OPC30/GGBS40/BOS30	2	30	40	30	0.15	18.07	25.48	3.54	4.45
OPC30/GGBS30/BOS40	3	30	30	40	0.15	24.32	34.75	4.58	5.39
OPC30/GGBS35/BOS35	4	30	35	35	0.15	23.85	34.36	3.29	4.38
OPC20/GGBS40/BOS40	5	20	40	40	0.15	18.51	31.43	3.50	4.09
OPC20/GGBS30/BOS50	6	20	30	50	0.15	23.61	35.11	3.34	5.41

Table 10.14: Mix proportion for (OPC-BOS-PG) paste mixtures

Mix Code	Mix	OPC (%)	BOS (%)	PG (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC30/BOS65/PG5	1	30	65	5	0.15	16.42	33.29	3.19	4.04
OPC40/BOS55/PG5	2	40	55	5	0.15	18.37	37.35	4.21	4.57
OPC50/BOS45/PG5	3	50	45	5	0.15	26.55	37.63	4.57	4.89
OPC60/BOS35/PG5	4	60	35	5	0.15	26.82	40.76	3.97	5.09
OPC70/BOS25/PG5	5	70	25	5	0.15	24.89	34.41	3.58	4.44
OPC50/BOS47/PG3	6	50	47	3	0.15	23.12	37.35	4.25	4.77
OPC30/BOS25/PG45	7	30	25	45	0.15	6.21	11.13	1.08	1.40
OPC50/BOS30/PG20	8	50	30	20	0.15	8.86	15.11	1.54	1.93
OPC30/BOS55/PG15	9	30	55	15	0.15	9.66	17.49	1.68	2.21

Table 10.15: Mix proportion for (OPC-ROSA-BOS) paste mixtures

Mix Code	Mix	OPC (%)	ROSA (%)	BOS (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC30/ROSA35/BOS35	1	30	35	35	0.15	20.93	25.14	3.55	4.13
OPC40/ROSA30/BOS30	2	40	30	30	0.15	27.70	34.79	3.84	4.60
OPC50/ROSA25/BOS25	3	50	25	25	0.15	28.29	34.81	4.12	4.79
OPC60/ROSA20/BOS20	4	60	20	20	0.15	30.77	41.11	4.84	4.94
OPC70/ROSA15/BOS15	5	70	15	15	0.15	28.05	37.95	4.45	4.67
OPC50/ROSA20/BOS30	6	50	20	30	0.15	26.21	34.57	3.85	4.65
OPC52/ROSA30/BOS18	7	52	30	18	0.15	31.47	41.80	4.30	5.14

Table 10.16: Mix proportion for (OPC-ROSA-PG) paste mixtures

Mix Code	Mix	OPC (%)	ROSA (%)	PG (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC40/ROSA55/PG5	1	40	55	5	0.15	7.77	15.02	2.00	2.23
OPC50/ROSA45/PG5	2	50	45	5	0.15	9.18	21.22	2.51	2.68
OPC60/ROSA35/PG5	3	60	35	5	0.15	12.17	22.82	3.09	3.22
OPC70/ROSA25/PG5	4	70	25	5	0.15	14.48	24.77	2.84	3.51
OPC80/ROSA15/PG5	5	80	15	5	0.15	20.79	30.78	3.14	3.90
OPC70/ROSA27/PG3	6	70	27	3	0.15	17.70	28.90	2.97	3.74
OPC80/ROSA17/PG3	7	80	17	3	0.15	21.47	32.11	3.27	4.03

Table 10.17: Mix proportion for (OPC-BOS) paste mixtures

Mix Code	Mix	OPC (%)	BOS (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
					14	28	14	28
OPC70/BOS30	1	70	30	0.15	33.66	48.13	4.45	4.92
OPC60/BOS40	2	60	40	0.15	42.61	55.68	4.99	5.32
OPC50/BOS50	3	50	50	0.15	37.39	49.57	4.88	5.18
OPC40/BOS60	4	40	60	0.15	33.87	45.60	4.24	5.16
OPC30/BOS70	5	30	70	0.15	31.15	40.48	3.71	4.43

Table 10.18: Mix proportion for (OPC-GGBS-PG) paste mixtures

Mix Code	Mix	OPC (%)	GGBS (%)	PG (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC80/GGBS15/PG5	1	80	15	5	0.15	12.35	22.19	2.95	3.29
OPC70/GGBS25/PG5	2	70	25	5	0.15	24.28	30.72	2.81	4.49
OPC60/GGBS35/PG5	3	60	35	5	0.15	20.13	27.39	2.78	3.71
OPC50/GGBS45/PG5	4	50	45	5	0.15	17.66	24.76	2.84	3.37
OPC40/GGBS55/PG5	5	40	55	5	0.15	13.38	22.85	2.52	3.32
OPC50/GGBS47/PG3	6	50	47	3	0.15	19.38	26.39	2.92	3.39
OPC40/GGBS15/PG45	7	40	15	45	0.15	8.34	10.77	1.16	1.51
OPC60/GGBS20/PG20	8	60	20	20	0.15	9.13	12.92	1.27	1.78
OPC40/GGBS45/PG15	9	40	45	15	0.15	13.88	17.23	1.93	2.42

Table 10.19: Mix proportion for (OPC-BPD-ROSA) paste mixtures

Mix Code	Mix	OPC (%)	BPD (%)	ROSA (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC70/BPD10/ROSA20	1	70	10	20	0.15	26.47	50.37	3.69	4.31
OPC60/BPD15/ROSA25	2	60	15	25	0.15	16.89	30.25	3.25	3.63
OPC50/BPD20/ROSA30	3	50	20	30	0.15	18.95	31.70	3.45	4.12
OPC40/BPD25/ROSA35	4	40	25	35	0.15	16.45	19.63	3.01	3.68
OPC30/BPD30/ROSA40	5	30	30	40	0.15	15.02	17.09	1.66	2.59
OPC40/BPD20/ROSA40	6	40	20	40	0.15	16.92	20.87	3.04	4.19
OPC30/BPD10/ROSA60	7	30	10	60	0.15	16.36	19.74	1.85	2.91
OPC50/BPD10/ROSA40	8	50	10	40	0.15	30.87	51.36	3.74	4.38

Table 10.20: Mix proportion for (OPC-BPD-GGBS) paste mixtures

Mix Code	Mix	OPC (%)	BPD (%)	GGBS (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC70/BPD10/GGBS20	1	70	10	20	0.15	22.09	30.43	3.38	4.55
OPC60/BPD10/GGBS30	2	60	10	30	0.15	21.72	27.76	3.17	3.73
OPC50/BPD10/GGBS40	3	50	7	43	0.15	11.98	21.56	2.91	3.28
OPC50/BPD5/GGBS45	4	50	5	45	0.15	30.29	39.76	2.46	5.86
OPC40/BPD5/GGBS55	5	40	5	55	0.15	28.57	34.62	2.48	3.92
OPC75/BPD5/GGBS20	6	75	5	20	0.15	30.94	48.76	3.91	5.87
OPC50/BPD20/GGBS30`	7	50	20	30	0.15	11.86	16.59	1.67	2.23
OPC40/BPD40/GGBS20	8	40	40	20	0.15	10.44	13.69	1.47	1.84

Table 10.21: Mix proportion for (OPC-BPD-BOS) paste mixtures

Mix Code	Mix	OPC (%)	BPD (%)	BOS (%)	W/B	Average compressive strength (MPa)		Average split tensile strength (MPa)	
						14	28	14	28
OPC80/BPD10/BOS10	1	80	10	10	0.15	21.13	33.62	3.11	3.18
OPC70/BPD10/BOS20	2	70	10	20	0.15	32.45	39.26	3.32	3.61
OPC60/BPD7/BOS33	3	60	7	33	0.15	33.94	40.56	3.56	4.51
OPC50/BPD5/BOS45	4	50	5	45	0.15	35.47	41.30	3.66	4.79
OPC40/BPD5/BOS55	5	40	5	55	0.15	36.55	47.43	4.04	5.16
OPC40/BPD50/BOS10	6	40	50	10	0.15	11.51	14.48	1.21	1.52
OPC40/BPD20/BOS40	7	40	20	40	0.15	18.45	21.23	1.94	2.21

10.3 Results of all mixes in first phase

Table 10.22: Mix 1 - Mixture design and stress for OPC-ROSA at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
ROSA30/OPC70									
ROSA	30%	Cubes	14	1	0.2318	44.75	1854.4	17.90	18.29
				2	0.2329	46.42	1863.2	18.57	
				3	0.2322	45.98	1857.6	18.39	
			28	1	0.2368	61.98	1894.4	24.79	24.21
				2	0.2363	60.24	1894.4	24.09	
				3	0.2352	59.35	1881.6	23.74	
OPC	70%	Blocks	14	1-II	2.9264	86.33	1925.3	3.62	3.63
				2-I	2.8159	83.25	1930.8	3.60	
				3-I	2.8335	85.06	1942.8	3.68	
W/B	0.15		28	1-I	2.8575	100.25	1959.3	4.33	4.25
				2-I	2.8587	99.06	1960.1	4.28	
				3-I	2.8494	96.00	1953.7	4.15	

Table 10.23: Mix 2 - Mixture design and stress for OPC-ROSA at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
ROSA40/OPC60									
ROSA	40%	Cubes	14	1	0.2138	43.79	1710.4	17.52	17.18
				2	0.2167	42.22	1733.6	16.89	
				3	0.2180	42.80	1744.0	17.12	
			28	1	0.2237	64.17	1789.6	25.67	24.94
				2	0.2223	60.20	1778.4	24.08	
				3	0.2229	62.65	1783.2	25.06	
OPC	60%	Blocks	14	1-II	2.8108	87.56	1849.2	3.67	3.61
				2-I	2.6956	83.37	1848.3	3.60	
				3-I	2.7219	82.31	1866.3	3.56	
W/B	0.15		28	1-I	2.7377	119.75	1877.1	5.18	5.22
				2-I	2.7523	124.50	1887.2	5.38	
				3-I	2.8060	117.69	1923.9	5.09	

Table 10.24: Mix 3 - Mixture design and stress for OPC-ROSA at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
ROSA50/OPC50									
ROSA	50%	Cubes	14	1	0.2131	43.31	1704.8	17.32	17.82
				2	0.2143	44.05	1714.4	17.62	
				3	0.2154	46.33	1723.2	18.53	
			28	1	0.2225	67.62	1780.0	27.05	26.38
				2	0.2206	65.18	1764.8	26.07	
				3	0.2198	65.05	1758.4	26.02	
OPC	50%	Blocks	14	1-II	2.7584	92.81	1814.7	3.89	3.88
				2-I	2.6582	90.06	1822.6	3.89	
				3-I	2.6338	89.19	1805.9	3.86	
W/B	0.15		28	1-I	2.6423	125.70	1811.7	5.27	5.42
				2-I	2.6501	126.41	1817.1	5.46	
				3-I	2.6534	127.80	1819.3	5.52	

Table 10.25: Mix 4 - Mixture design and stress for OPC-ROSA at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
ROSA60/OPC40									
ROSA	60%	Cubes	14	1	0.2120	41.66	1696.0	16.66	15.85
				2	0.2113	38.37	1690.4	15.35	
				3	0.2115	38.84	1692.0	15.54	
			28	1	0.2145	57.67	1716.0	23.07	23.24
				2	0.2136	56.98	1708.8	22.79	
				3	0.2163	59.67	1730.4	23.87	
OPC	40%	Blocks	14	1-II	2.5600	67.81	1758.2	2.84	2.89
				2-I	2.4990	66.69	1713.5	2.88	
				3-I	2.5825	68.81	1770.7	2.97	
W/B	0.15		28	1-I	2.5428	72.80	1743.5	3.15	3.72
				2-I	2.5632	77.44	1757.5	3.35	
				3-I	2.5491	76.62	1747.8	3.31	

Table 10.26: Mix 5 - Mixture design and stress for OPC-ROSA at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
ROSA70/OPC30									
ROSA	70%	Cubes	14	1	0.1953	30.48	1562.4	12.19	11.53
				2	0.1942	27.54	1553.6	11.02	
				3	0.1948	28.42	1558.4	11.37	
	30%		28	1	0.1975	41.22	1580.0	16.49	16.82
				2	0.1995	43.92	1596.0	17.57	
OPC				3	0.1960	41.00	1568.0	16.40	
	30%	Blocks	14	1-II	2.6255	50.50	1727.3	2.12	2.23
				2-I	2.4905	53.56	1707.6	2.29	
				3-I	2.4805	52.56	1700.8	2.27	
W/B	0.15		28	1-I	2.4963	66.69	1711.6	2.88	2.90
				2-I	2.5096	65.37	1720.7	2.83	
				3-I	2.5123	69.50	1722.6	3.00	

Table 10.27: Mix 1 - Mixture design and stress for OPC-GGBS-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/GGBS30/ BOS30									
OPC	40%	Cubes	14	1	0.2580	40.65	2064.0	16.23	17.37
				2	0.2607	45.79	2085.6	18.32	
				3	0.2605	43.82	2084.0	17.53	
GGBS	30%		28	1	0.2673	57.90	2140.8	23.16	23.24
				2	0.2655	56.42	2124.0	22.57	
				3	0.2686	59.94	2148.8	23.98	
BOS	30%	Blocks	14	1-I	3.1495	73.62	2159.5	3.18	3.28
				2-I	3.1540	75.69	2162.6	3.27	
				3-I	3.1575	78.15	2164.9	3.38	
W/B	0.15		28	1-I	3.2015	96.63	2195.2	4.18	4.30
				2-II	3.2405	98.72	2181.9	4.27	
				3-II	3.2765	102.87	2198.6	4.45	

Table 10.28: Mix 2 - Mixture design and stress for OPC-GGBS-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/GGBS40/ BOS30									
OPC	30%	Cubes	14	1	0.2547	45.32	2037.6	18.13	18.07
				2	0.2545	43.04	2036.0	17.22	
				3	0.2578	47.17	2062.4	18.87	
GGBS	40%		28	1	0.2646	65.56	2116.8	26.22	25.48
				2	0.2643	63.25	2114.4	25.30	
				3	0.2633	62.28	2106.4	24.94	
BOS	30%	Blocks	14	1-I	3.0805	80.44	2112.2	3.48	3.54
				2-I	3.0930	83.19	2120.8	3.59	
W/B	0.15		28	1-I	3.0950	105.06	2122.1	4.54	4.45
				2-I	3.0780	103.81	2110.5	4.49	
				3-I	3.1035	100.00	2127.9	4.32	

Table 10.29: Mix 3 - Mixture design and stress for OPC-GGBS-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/GGBS30/ BOS40									
OPC	30%	Cubes	14	1	0.2682	58.92	2145.6	23.57	24.32
				2	0.2697	62.10	2157.6	24.84	
				3	0.2695	61.35	2156.0	24.54	
GGBS	30%		28	1	0.2754	85.39	2203.2	34.16	34.75
				2	0.2778	88.00	2222.4	35.2	
				3	0.2765	87.22	2212.0	34.89	
BOS	40%	Blocks	14	1-I	3.2430	108.69	2223.6	4.69	4.58
				2-I	3.2495	105.31	2228.1	4.55	
				3-II	3.4085	107.62	2242.4	4.51	
W/B	0.15		28	1-I	3.2665	125.37	2239.7	5.42	5.39
				2-I	3.2495	122.31	2228.1	5.29	
				3-I	3.2740	126.05	2244.9	5.45	

Table 10.30: Mix 4 - Mixture design and stress for OPC-GGBS-BOS at 14 and 28 days

Mix code OPC30/GGBS35/ BOS35		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	30%	Cubes	14	1	0.2566	58.82	2052.8	23.53	23.85
				2	0.2586	61.35	2068.8	24.54	
				3	0.2553	58.67	2042.4	23.47	
GGBS	35%		28	1	0.2665	88.23	2132.0	35.29	34.36
				2	0.2630	84.29	2104.0	33.72	
				3	0.2658	85.20	2126.4	34.08	
BOS	35%	Blocks	14	1-I	3.1065	73.69	2130.0	3.19	3.29
				2-I	3.1110	78.19	2133.1	3.38	
				3-I	3.1710	76.44	2174.2	3.30	
W/B	0.15		28	1-I	3.1800	100.56	2180.4	4.35	4.38
				2-II	3.2850	102.12	2171.2	4.28	
				3-I	3.1970	104.62	2192.1	4.52	

Table 10.31: Mix 5 - Mixture design and stress for OPC-GGBS-BOS at 14 and 28 days

Mix code OPC20/GGBS40/ BOS40		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	20%	Cubes	14	1	0.2567	47.29	2053.6	18.92	18.51
				2	0.2538	45.08	2030.4	18.03	
				3	0.2563	46.42	2050.4	18.57	
GGBS	40%		28	1	0.2665	77.63	2132.0	31.05	31.43
				2	0.2650	77.07	2120.0	30.83	
				3	0.2672	81.04	2137.6	32.42	
BOS	40%	Blocks	14	1-I	3.1475	78.94	2158.1	3.41	3.50
				2-I	3.1580	80.44	2165.3	3.48	
				3-II	3.2320	86.05	2166.3	3.61	
W/B	0.15		28	1-I	3.1795	96.81	2180.1	4.19	4.09
				2-I	3.1765	92.06	2178.0	3.98	
				3-I	3.1670	95.00	2171.5	4.11	

Table 10.32: Mix 6 - Mixture design and stress for OPC-GGBS-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC20/GGBS30/BOS50									
OPC	20%	Cubes	14	1	0.2653	61.23	2122.4	24.49	23.61
				2	0.2621	58.04	2096.8	23.22	
				3	0.2608	57.78	2086.4	23.11	
GGBS	30%		28	1	0.2685	85.99	2148.0	34.39	35.11
				2	0.2720	87.43	2176.0	34.97	
				3	0.2730	89.90	2184.0	35.96	
BOS	50%	Blocks	14	1-I	3.2626	76.92	2237.1	3.33	3.34
				2-I	3.2656	80.85	2239.1	3.49	
				3-I	3.2595	74.32	2234.9	3.21	
W/B	0.15		28	1-I	3.2890	130.25	2255.1	5.63	5.41
				2-II	3.4615	126.63	2277.3	5.31	
				3-II	3.4600	126.00	2276.3	5.28	

Table 10.33: Mix 1 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/BOS65/PG5									
OPC	30%	Cubes	14	1	0.2843	39.26	2274.4	15.70	16.42
				2	0.2866	42.04	2292.8	16.82	
				3	0.2854	41.86	2283.2	16.74	
BOS	65%		28	1	0.2955	85.79	2364.0	34.32	33.29
				2	0.2938	81.12	2350.4	32.45	
				3	0.2950	82.75	2360.0	33.10	
PG	5%	Blocks	14	1-II	3.6124	71.87	2386.6	3.01	3.19
				2-I	3.4958	76.12	2396.9	3.29	
				3-I	3.4834	75.62	2388.4	3.27	
W/B	0.15		28	1-I	3.4918	93.80	2394.2	4.06	4.04
				2-I	3.4980	95.67	2398.5	4.14	
				3-I	3.4875	90.73	2391.3	3.92	

Table10.34: Mix 2 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code OPC40/BOS55/ PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	40%	Cubes	14	1	0.2751	47.12	2200.8	18.85	18.37
				2	0.2745	42.05	2196.0	16.82	
				3	0.2762	48.62	2209.6	19.45	
BOS	55%		28	1	0.2845	93.88	2276.0	37.55	37.35
				2	0.2860	94.23	2288.0	37.69	
				3	0.2842	92.05	2273.6	36.82	
PG	5%	Blocks	14	1-I	3.3934	96.37	2326.7	4.17	4.21
				2-I	3.4076	95.00	2336.5	4.11	
				3-I	3.4026	100.94	2333.0	4.36	
W/B	0.15		28	1-II	3.5404	110.54	2359.2	4.63	4.57
				2-I	3.4420	106.29	2360.1	4.59	
				3-I	3.4150	104.00	2341.5	4.49	

Table 10.35: Mix 3 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code OPC50/BOS45/ PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa))
OPC	50%	Cubes	14	1	0.2735	67.63	2188.0	27.05	26.55
				2	0.2716	65.00	2172.8	26.00	
				3	0.2733	66.52	2186.4	26.61	
BOS	45%		28	1	0.2768	95.79	2214.4	38.32	37.63
				2	0.2765	94.32	2212.0	37.73	
				3	0.2751	92.08	2200.8	36.82	
PG	5%	Blocks	14	1-I	3.3205	108.12	2276.7	4.67	4.57
				2-I	3.3440	106.56	2292.9	4.61	
				3-I	3.3500	102.69	2296.9	4.44	
W/B	0.15		28	1-II	3.5620	116.50	2343.4	4.88	4.89
				2-I	3.3970	113.25	2329.2	4.89	
				3-I	3.4490	113.44	2364.9	4.90	

Table 10.36: Mix 4 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/BOS35/PG5									
OPC	60%	Cubes	14	1	0.2708	65.84	2166.4	26.34	26.82
				2	0.2736	69.33	2188.8	27.73	
				3	0.2717	65.99	2173.6	26.39	
BOS	35%		28	1	0.2780	104.67	2224.0	41.87	40.76
				2	0.2765	102.35	2212.0	40.94	
				3	0.2750	98.70	2200.0	39.48	
PG	5%	Blocks	14	1-II	3.4071	90.31	2241.5	3.78	3.97
				2-I	3.2553	95.62	2232.0	4.13	
				3-I	3.2650	92.40	2238.7	3.99	
W/B	0.15		28	1-I	3.3081	117.67	2268.2	5.09	5.09
				2-I	3.3117	120.54	2270.7	5.21	
				3-I	3.2711	115.17	2242.9	4.98	

Table 10.37: Mix 5 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/BOS25/PG5									
OPC	70%	Cubes	14	1	0.2639	61.36	2111.2	24.54	24.89
				2	0.2672	65.24	2137.6	26.09	
				3	0.2609	60.07	2087.2	24.03	
BOS	25%		28	1	0.2720	84.44	2176.0	33.78	34.41
				2	0.2760	88.34	2208.0	35.34	
				3	0.2725	85.31	2180.0	34.12	
PG	5%	Blocks	14	1-II	3.2981	85.25	2169.8	3.57	3.58
				2-I	3.1602	81.00	2166.8	3.50	
				3-I	3.2098	84.56	2200.8	3.66	
W/B	0.15		28	1-I	3.2157	100.73	2204.9	4.35	4.44
				2-I	3.2286	101.85	2213.7	4.40	
				3-I	3.2158	105.48	2204.9	4.56	

Table 10.38: Mix 6 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BOS47/ PG3									
OPC	50%	Cubes	14	1	0.2825	55.78	2260.0	22.31	23.12
				2	0.2840	59.33	2272.0	23.73	
				3	0.2835	58.28	2268.0	23.31	
BOS	47%		28	1	0.2890	95.62	2312.0	38.25	37.35
				2	0.2885	92.45	2308.0	36.98	
				3	0.2880	92.07	2304.0	36.83	
PG	3%	Blocks	14	1-I	3.4110	95.22	2338.8	4.13	4.25
				2-I	3.4285	98.38	2350.8	4.27	
				3-I	3.4325	100.52	2353.5	4.36	
W/B	0.15		28	1-I	3.4800	109.41	2386.1	4.73	4.77
				2-I	3.4895	112.73	2392.6	4.89	
				3-I	3.4955	108.60	2396.7	4.71	

Table 10.39: Mix 7 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/BOS25/ PG45									
OPC	30%	Cubes	14	1	0.2574	15.25	2059	6.10	6.21
				2	0.2608	15.88	2086	6.35	
				3	0.2596	15.45	2077	6.18	
BOS	25%		28	1	0.2653	27.13	2122	10.85	11.13
				2	0.2681	28.05	2145	11.22	
				3	0.2664	27.63	2131	11.05	
PG	45%	Blocks	14	1-I	3.0888	24.29	2118	1.05	1.08
				2-I	3.1296	24.98	2146	1.08	
				3-I	3.1152	25.91	2136	1.12	
W/B	0.15		28	1-I	3.1836	32.85	2183	1.42	1.40
				2-I	3.2172	31.69	2206	1.37	
				3-I	3.1968	32.15	2192	1.39	

Table 10.40: Mix 8 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BOS30/ PG20									
OPC	50%	Cubes	14	1	0.2607	21.75	2086	8.70	8.86
				2	0.2623	22.63	2098	9.05	
				3	0.2614	22.10	2091	8.84	
BOS	30%		28	1	0.2703	37.58	2162	15.03	15.11
				2	0.2718	36.98	2174	14.79	
				3	0.2712	38.83	2170	15.53	
PG	20%	Blocks	14	1-I	3.1284	37.70	2145	1.63	1.54
				2-I	3.1476	32.85	2158	1.42	
				3-I	3.1368	36.32	2151	1.57	
W/B	0.15		28	1-I	3.2436	45.80	2224	1.98	1.93
				2-I	3.2616	43.72	2236	1.89	
				3-I	3.2544	44.41	2232	1.92	

Table 10.41: Mix 9 - Mixture design and stress for OPC-BOS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/BOS55/ PG15									
OPC	30%	Cubes	14	1	0.2742	25.25	2194	10.10	9.66
				2	0.2710	24.33	2168	9.73	
				3	0.2705	22.88	2164	9.15	
BOS	55%		28	1	0.2786	44.05	2229	17.62	17.49
				2	0.2794	44.75	2235	17.90	
				3	0.2773	42.45	2218	16.98	
PG	15%	Blocks	14	1-I	3.2904	40.48	2256	1.75	1.68
				2-I	3.2520	38.39	2230	1.66	
				3-I	3.2460	37.94	2226	1.64	
W/B	0.15		28	1-I	3.3432	54.82	2292	2.37	2.21
				2-I	3.3528	50.43	2299	2.18	
				3-I	3.3276	47.88	2282	2.07	

Table 10.42: Mix 1 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code OPC30/ROSA35/ BOS35		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	30%	Cubes	14	1	0.2381	52.48	1904.8	20.99	20.93
				2	0.2376	52.79	1900.8	21.12	
				3	0.2369	51.67	1895.2	20.67	
ROSA	35%		28	1	0.2420	62.73	1936.0	25.09	25.14
				2	0.2440	63.48	1952.0	25.39	
				3	0.2428	62.33	1942.4	24.93	
BOS	35%	Blocks	14	1-I	2.9253	79.56	2005.8	3.44	3.55
				2-I	2.9377	84.69	2014.3	3.66	
				3-I	2.9452	82.31	2019.4	3.56	
W/B	0.15		28	1-II	3.0235	94.42	2039.1	3.96	4.13
				2-I	2.9581	99.04	2028.3	4.28	
				3-I	2.9500	96.33	2022.7	4.16	

Table 10.43: Mix 2 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code OPC40/ROSA30/ BOS30		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	40%	Cubes	14	1	0.2477	71.42	1981.6	28.57	27.70
				2	0.2469	68.27	1975.2	27.31	
				3	0.2463	68.03	1970.4	27.21	
ROSA	30%		28	1	0.2555	85.43	2044.0	34.17	34.79
				2	0.2580	87.92	2064.0	35.17	
				3	0.2562	87.54	2049.6	35.02	
BOS	30%	Blocks	14	1-II	3.0965	88.06	2037.2	3.69	3.84
				2-I	2.9370	91.31	2013.8	3.95	
				3-I	2.9870	89.87	2048.1	3.89	
W/B	0.15		28	1-I	2.9775	110.00	2041.6	4.76	4.60
				2-I	2.9780	105.19	2041.9	4.55	
				3-I	2.9820	103.75	2044.7	4.49	

Table 10.44: Mix 3 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/ROSA25/BOS25									
OPC	50%	Cubes	14	1	0.2422	72.36	1937.6	28.94	28.29
				2	0.2436	69.02	1948.8	27.61	
				3	0.2441	70.84	1952.8	28.34	
ROSA	25%		28	1	0.2535	84.35	2028.0	33.74	34.81
				2	0.2565	89.23	2052.0	35.69	
				3	0.2548	87.52	2038.4	35.01	
BOS	25%	Blocks	14	1-II	3.1075	97.56	2130.7	4.09	4.12
				2-I	2.9980	96.87	2055.6	4.19	
				3-I	2.9820	94.52	2044.7	4.09	
W/B	0.15		28	1-I	3.0170	110.33	2068.6	4.77	4.79
				2-I	3.0120	109.07	2065.2	4.72	
				3-I	3.0880	112.87	2117.3	4.88	

Table 10.45: Mix 4 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/ROSA20/BOS20									
OPC	60%	Cubes	14	1	0.2463	76.92	1970.4	30.77	30.77
				2	0.2470	78.35	1976.0	31.34	
				3	0.2455	75.48	1964.0	30.19	
ROSA	20%		28	1	0.2550	103.73	2040.0	41.49	41.11
				2	0.2490	100.67	1992.0	40.27	
				3	0.2575	103.92	2060.0	41.57	
BOS	20%	Blocks	14	1-I	3.0432	113.86	2086.6	4.92	4.84
				2-I	3.0361	110.19	2081.7	4.76	
				3-I	3.0106	96.56	2064.3	4.17	
W/B	0.15		28	1-II	3.1665	114.10	2171.2	4.78	4.94
				2-I	3.0719	120.17	2106.3	5.19	
				3-I	3.0595	112.48	2097.8	4.86	

Table 10.46: Mix 5 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/ROSA15/ BOS15									
OPC	70%	Cubes	14	1	0.2586	71.36	2068.8	28.54	28.05
				2	0.2575	68.22	2060.0	27.29	
				3	0.2583	70.80	2066.4	28.32	
ROSA	15%		28	1	0.2636	94.10	2108.8	37.64	37.95
				2	0.2622	91.88	2097.6	36.75	
				3	0.2658	98.67	2126.4	39.47	
BOS	15%	Blocks	14	1-I	3.0810	105.06	2112.5	4.54	4.45
				2-I	3.0583	104.75	2096.9	4.53	
				3-I	3.0540	99.31	2094.0	4.29	
W/B	0.15		28	1-II	3.2192	113.04	2137.9	4.74	4.67
				2-I	3.1127	107.85	2134.3	4.66	
				3-I	3.1013	106.72	2126.5	4.61	

Table 10.47: Mix 6 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/ROSA20/ BOS30									
OPC	50%	Cubes	14	1	0.2585	68.00	2068.0	27.20	26.21
				2	0.2560	63.38	2048.0	25.35	
				3	0.2555	65.22	2044.0	26.09	
ROSA	20%		28	1	0.2695	87.52	2156.0	35.01	34.57
				2	0.2675	85.36	2140.0	34.14	
				3	0.2665	86.40	2132.0	34.56	
BOS	30%	Blocks	14	1-I	3.1880	87.79	2185.9	3.79	3.85
				2-I	3.1945	89.61	2190.4	3.89	
				3-I	3.1905	89.44	2187.6	3.88	
W/B	0.15		28	1-I	3.2090	110.79	2200.3	4.79	4.65
				2-III	3.1720	106.20	2225.9	4.60	
				3-III	3.1705	105.35	2224.9	4.57	

Table 10.48: Mix 7 - Mixture design and stress for OPC-ROSA-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC52/ROSA30/ BOS18									
OPC	52%	Cubes	14	1	0.2350	76.55	1880.0	30.62	31.47
				2	0.2385	79.07	1908.0	31.63	
				3	0.2375	80.43	1900.0	32.17	
ROSA	30%		28	1	0.2455	105.26	1964.0	42.10	41.80
				2	0.2435	103.78	1948.0	41.51	
				3	0.2440	104.50	1952.0	41.80	
BOS	18%	Blocks	14	1-I	2.9750	100.30	2039.9	4.34	4.30
				2-I	2.9705	98.77	2036.8	4.27	
				3-I	2.9735	99.54	2038.8	4.30	
W/B	0.15		28	1-I	2.9905	116.80	2050.5	4.89	5.14
				2-I	2.9930	118.04	2052.2	5.21	
				3-I	2.9945	120.32	2053.2	5.31	

Table 10.49: Mix 1 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/ROSA55/ PG5									
OPC	40%	Cubes	14	1	0.1985	21.29	1588.0	8.52	7.77
				2	0.1953	19.60	1562.4	7.84	
				3	0.1949	17.35	1559.2	6.94	
ROSA	55%		28	1	0.2045	39.42	1636.0	15.77	15.02
				2	0.2030	33.67	1624.0	13.47	
				3	0.2035	39.54	1628.0	15.82	
PG	5%	Blocks	14	1-I	2.4927	47.54	1709.2	2.06	2.00
				2-I	2.5054	42.73	1717.9	1.85	
				3-I	2.5043	48.29	1717.1	2.09	
W/B	0.15		28	1-II	2.5875	52.41	1722.3	2.19	2.23
				2-I	2.5132	50.36	1723.2	2.18	
				3-I	2.5159	53.92	1725.1	2.33	

Table 10.50: Mix 2 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code OPC50/ROSA45/PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	50%	Cubes	14	1	0.2085	24.42	1668.0	9.77	9.18
				2	0.2047	20.04	1637.6	8.02	
				3	0.2063	24.35	1650.4	9.74	
ROSA	45%		28	1	0.2135	54.67	1708.0	21.87	21.22
				2	0.2095	49.79	1676.0	19.92	
				3	0.2140	54.67	1712.0	21.87	
PG	5%	Blocks	14	1-I	2.5945	56.17	1778.9	2.43	2.51
				2-I	2.5824	58.42	1770.7	2.53	
				3-I	2.5863	59.29	1773.3	2.56	
W/B	0.15		28	1-II	2.6946	62.82	1792.8	2.63	2.68
				2-I	2.6292	63.17	1802.7	2.73	
				3-I	2.6039	62.04	1785.4	2.68	

Table 10.51: Mix 3 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code OPC60/ROSA35/PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	60%	Cubes	14	1	0.2115	30.66	1692.0	12.26	12.17
				2	0.2109	28.42	1687.2	11.37	
				3	0.2135	32.17	1708.0	12.87	
ROSA	35%		28	1	0.2260	56.54	1808.0	22.62	22.82
				2	0.2280	60.29	1824.0	24.12	
				3	0.2235	54.32	1788.0	21.73	
PG	5%	Blocks	14	1-I	2.6649	69.60	1827.2	3.01	3.09
				2-I	2.6505	72.82	1817.4	3.15	
				3-I	2.6659	71.92	1827.9	3.11	
W/B	0.15		28	1-II	2.7575	75.48	1834.1	3.16	3.22
				2-I	2.6981	76.17	1849.9	3.29	
				3-I	2.6719	74.35	1832.0	3.21	

Table 10.52: Mix 4 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code OPC70/ROSA25/PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	70%	Cubes	14	1	0.2205	32.44	1764.0	12.98	14.48
				2	0.2220	35.92	1776.0	14.37	
				3	0.2264	40.23	1811.2	16.09	
ROSA	25%		28	1	0.2282	65.67	1825.6	26.27	24.77
				2	0.2271	60.23	1816.8	24.09	
				3	0.2254	59.85	1803.2	23.94	
PG	5%	Blocks	14	1-I	2.7551	67.92	1889.1	2.94	2.84
				2-I	2.7222	65.54	1866.5	2.83	
				3-I	2.7120	63.31	1859.5	2.74	
W/B	0.15		28	1-II	2.8649	81.50	1964.4	3.42	3.51
				2-I	2.7589	80.72	1891.7	3.49	
				3-I	2.8110	84.04	1927.4	3.63	

Table 10.53: Mix 5 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code OPC80/ROSA15/PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	80%	Cubes	14	1	0.2340	55.54	1896.0	22.22	20.79
				2	0.2325	47.17	1860.0	18.87	
				3	0.2320	53.22	1856.0	21.29	
ROSA	15%		28	1	0.2380	78.92	1904.0	31.57	30.78
				2	0.2374	75.38	1899.2	30.15	
				3	0.2379	76.55	1903.2	30.62	
PG	5%	Blocks	14	1-I	2.8549	72.17	1957.5	3.12	3.14
				2-I	2.8074	70.29	1924.9	3.04	
				3-I	2.8561	75.73	1958.3	3.27	
W/B	0.15		28	1-II	3.0070	93.85	1978.3	3.93	3.90
				2-I	2.8688	90.35	1967.0	3.91	
				3-I	2.8850	89.21	1978.1	3.86	

Table 10.54: Mix 6 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/ROSA27/ PG3									
OPC	70%	Cubes	14	1	0.2265	40.22	1812.0	16.09	17.70
				2	0.2270	42.75	1816.0	17.10	
				3	0.2285	45.08	1828.0	18.30	
ROSA	27%		28	1	0.2350	72.33	1880.0	28.93	28.90
				2	0.2320	70.40	1856.0	28.16	
				3	0.2355	74.06	1884.0	29.62	
PG	3%	Blocks	14	1-I	2.8530	70.24	1956.2	3.04	2.97
				2-I	2.8445	67.51	1950.4	2.92	
				3-I	2.8485	68.22	1953.1	2.95	
W/B	0.15		28	1-I	2.8615	86.54	1962.0	3.74	3.74
				2-II	2.9700	88.56	1953.9	3.71	
				3-II	2.9725	89.73	1955.6	3.76	

Table 10.55: Mix 7 - Mixture design and stress for OPC-ROSA-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC80/ROSA17/ PG3									
OPC	80%	Cubes	14	1	0.2300	54.30	1840.0	21.72	21.47
				2	0.2285	52.75	1828.0	21.10	
				3	0.2290	54.00	1832.0	21.60	
ROSA	17%		28	1	0.2365	79.26	1892.0	31.71	32.11
				2	0.2370	80.08	1896.0	32.03	
				3	0.2370	81.44	1896.0	32.58	
PG	3%	Blocks	14	1-I	2.8220	75.03	1934.9	3.24	3.27
				2-I	2.8300	76.25	1940.4	3.29	
				3-I	2.8275	76.00	1938.7	3.28	
W/B	0.15		28	1-I	2.8550	94.15	1957.6	4.15	4.03
				2-I	2.8495	92.38	1953.8	3.99	
				3-II	2.8760	94.56	1962.1	3.96	

Table 10.56: Mix 1 - Mixture design and stress for OPC-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/BOS30									
OPC	70%	Cubes	14	1	0.2766	88.42	2212.8	35.37	33.66
				2	0.2759	80.75	2207.2	32.30	
				3	0.2756	83.26	2204.8	33.30	
			28	1	0.2810	121.29	2248.0	48.52	48.13
				2	0.2805	115.34	2244.0	46.14	
BOS	30%			3	0.2834	124.29	2267.2	49.72	
		Blocks	14	1-I	3.3302	100.66	2283.4	4.35	4.45
				2-I	3.3633	105.79	2306.1	4.57	
				3-I	3.3484	102.20	2295.9	4.42	
W/B	0.15		28	1-II	3.4838	113.98	2328.7	4.78	4.92
				2-I	3.3800	112.88	2317.5	4.98	
				3-I	3.3849	115.41	2320.9	4.99	

Table 10.57: Mix 2 - Mixture design and stress for OPC-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/BOS40									
OPC	60%	Cubes	14	1	0.2832	106.23	2265.6	42.49	42.61
				2	0.2864	108.98	2291.2	43.59	
				3	0.2828	104.41	2262.4	41.76	
			28	1	0.2900	135.73	2320.0	54.29	55.68
				2	0.2930	142.23	2344.0	56.89	
BOS	40%			3	0.2916	139.67	2332.8	55.87	
		Blocks	14	1-II	3.5501	115.37	2345.6	4.99	4.99
				2-I	3.4290	113.88	2351.1	4.92	
				3-I	3.4286	116.80	2350.9	5.05	
W/B	0.15		28	1-I	3.4091	123.66	2337.5	5.18	5.32
				2-I	3.4089	125.41	2337.4	5.42	
				3-I	3.4102	124.20	2338.3	5.37	

Table 10.58: Mix 3 - Mixture design and stress for OPC-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BOS50									
OPC	50%	Cubes	14	1	0.2925	92.65	2340.0	37.06	37.39
				2	0.2940	97.46	2352.0	38.98	
				3	0.2899	90.33	2312.0	36.13	
			28	1	0.3005	123.80	2404.0	49.52	49.57
				2	0.3010	125.64	2408.0	50.26	
BOS	50%			3	0.2985	122.35	2388.0	48.94	
		Blocks	14	1-I	3.4791	115.92	2385.5	5.01	4.88
				2-I	3.4642	110.79	2375.3	4.79	
				3-I	3.4746	111.92	2382.4	4.84	
W/B	0.15		28	1-II	3.6193	120.33	2381.1	5.04	5.18
				2-I	3.4856	122.41	2389.9	5.29	
				3-I	3.4847	120.52	2389.3	5.21	

Table 10.59: Mix 4 - Mixture design and stress for OPC-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BOS60									
OPC	40%	Cubes	14	1	0.2887	88.32	2309.6	35.33	33.87
				2	0.2871	85.20	2296.8	34.08	
				3	0.2869	80.48	2295.2	32.19	
			28	1	0.3015	116.37	2412.0	46.55	45.6
				2	0.2980	113.22	2384.0	45.29	
BOS	60%			3	0.2970	112.41	2376.0	44.96	
		Blocks	14	1-I	3.4623	100.04	2373.9	4.32	4.24
				2-I	3.4115	96.54	2339.1	4.17	
				3-I	3.4312	97.80	2352.7	4.23	
W/B	0.15		28	1-II	3.5929	117.79	2393.8	4.94	5.16
				2-I	3.4795	123.85	2385.8	5.35	
				3-I	3.3974	119.73	2329.5	5.18	

Table 10.60: Mix 5 - Mixture design and stress for OPC-BOS at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/BOS70									
OPC	30%	Cubes	14	1	0.3022	77.08	2417.6	30.83	31.15
				2	0.3010	76.36	2408.0	30.54	
				3	0.3050	80.24	2440.0	32.09	
			28	1	0.3080	99.25	2464.0	39.70	40.48
				2	0.3090	100.44	2472.0	40.18	
BOS	70%			3	0.3105	103.88	2484.0	41.55	
		Blocks	14	1-I	3.4551	84.35	2369.0	3.65	3.71
				2-I	3.4561	85.79	2369.7	3.71	
				3-I	3.4777	87.38	2384.5	3.78	
W/B	0.15		28	1-II	3.5994	104.85	2388.0	4.39	4.43
				2-I	3.4965	101.73	2397.4	4.39	
				3-I	3.4919	104.48	2394.3	4.52	

Table 10.61: Mix 1 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC80/GGBS15/ PG5									
OPC	80%	Cubes	14	1	0.2450	32.61	1960.0	13.04	12.35
				2	0.2403	29.98	1922.4	11.99	
				3	0.2475	30.04	1980.0	12.02	
GGBS	15%		28	1	0.2565	58.44	2052.0	23.38	22.19
				2	0.2520	54.72	2016.0	21.89	
				3	0.2520	53.29	2016.0	21.32	
PG	5%	Blocks	14	1-I	2.9824	68.29	2044.9	2.95	2.95
				2-I	2.9324	67.48	2010.6	2.92	
				3-I	2.9403	69.37	2016.1	2.99	
W/B	0.15		28	1-II	3.0779	75.54	2084.9	3.17	3.29
				2-I	2.9981	76.17	2055.7	3.29	
				3-I	3.0471	79.22	2089.3	3.42	

Table 10.62: Mix 2 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/GGBS25/PG5									
OPC	70%	Cubes	14	1	0.2398	63.48	1918.4	25.39	24.28
				2	0.2324	58.07	1859.2	23.23	
				3	0.2386	60.52	1908.8	24.21	
GGBS	25%		28	1	0.2440	77.40	1952.0	30.96	30.72
				2	0.2470	79.66	1976.0	31.86	
				3	0.2423	73.32	1938.4	29.33	
PG	5%	Blocks	14	1-I	2.9086	66.76	1994.3	2.89	2.81
				2-I	2.9049	63.48	1991.8	2.74	
				3-I	2.9097	64.67	1995.1	2.79	
W/B	0.15		28	1-II	3.0305	105.35	1993.8	4.41	4.49
				2-I	2.9445	106.23	2018.9	4.59	
				3-I	2.9101	103.82	1995.4	4.49	

Table 10.63: Mix 3 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/GGBS35/PG5									
OPC	60%	Cubes	14	1	0.2287	48.18	1829.6	19.27	20.13
				2	0.2335	52.37	1868.0	20.95	
				3	0.2308	50.41	1846.4	20.16	
GGBS	35%		28	1	0.2365	65.66	1892.0	26.26	27.39
				2	0.2395	68.09	1916.0	27.24	
				3	0.2400	71.72	1920.0	28.69	
PG	5%	Blocks	14	1-I	2.8524	66.50	1955.8	2.87	2.78
				2-I	2.8646	62.98	1964.2	2.72	
				3-I	2.8429	63.48	1949.3	2.74	
W/B	0.15		28	1-II	2.9590	86.30	1976.7	3.62	3.71
				2-I	2.8892	88.42	1981.0	3.82	
				3-I	2.8785	85.35	1973.7	3.69	

Table 10.64: Mix 4 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code OPC50/GGBS45/PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	50%	Cubes	14	1	0.2280	41.85	1824.0	16.74	17.66
				2	0.2335	48.00	1868.0	19.2	
				3	0.2294	42.60	1835.2	17.04	
GGBS	45%		28	1	0.2370	61.44	1896.0	24.58	24.76
				2	0.2360	60.79	1888.0	24.32	
				3	0.2400	63.48	1920.0	25.39	
PG	5%	Blocks	14	1-I	2.7790	62.48	1905.5	2.70	2.84
				2-I	2.7948	66.60	1916.3	2.88	
				3-I	2.8150	67.73	1930.1	2.93	
W/B	0.15		28	1-II	2.9438	77.79	1936.7	3.26	3.37
				2-I	2.8767	80.29	1972.5	3.47	
				3-I	2.8233	78.35	1935.8	3.39	

Table 10.65: Mix 5 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code OPC40/GGBS55/PG5		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	40%	Cubes	14	1	0.2245	34.92	1796.0	13.97	13.38
				2	0.2240	34.60	1792.0	13.84	
				3	0.2225	30.82	1780.0	12.33	
GGBS	55%		28	1	0.2315	59.17	1582.0	23.67	22.85
				2	0.2335	56.48	1868.0	22.59	
				3	0.2295	55.73	1836.0	22.29	
PG	5%	Blocks	14	1-I	2.7942	56.67	1915.9	2.45	2.52
				2-I	2.7870	59.29	1910.9	2.56	
				3-I	2.7648	59.33	1895.7	2.56	
W/B	0.15		28	1-II	2.8938	77.92	1943.8	3.27	3.32
				2-I	2.8366	78.52	1944.9	3.39	
				3-I	2.8304	76.04	1940.7	3.29	

Table 10.66: Mix 6 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/GGBS4/ PG3									
OPC	50%	Cubes	14	1	0.2305	46.22	1844.0	18.49	19.38
				2	0.2330	48.42	1864.0	19.37	
				3	0.2350	50.73	1880.0	20.29	
GGBS	47%		28	1	0.2400	64.88	1920.0	25.95	26.39
				2	0.2405	65.77	1924.0	26.31	
				3	0.2420	67.29	1936.0	26.92	
PG	3%	Blocks	14	1-I	2.9735	66.58	20.38.8	2.88	2.92
				2-I	2.9840	68.41	2046.0	2.96	
				3-I	2.9775	67.20	2041.6	2.91	
W/B	0.15		28	1-I	2.9875	78.37	2048.4	3.39	3.39
				2-II	3.0670	79.88	2052.8	3.35	
				3-II	3.0675	81.62	2055.1	3.42	

Table 10.67: Mix 7 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/GGBS15/ PG45									
OPC	40%	Cubes	14	1	0.2345	21.88	1876	8.75	8.34
				2	0.2305	19.85	1844	7.94	
				3	0.2320	20.83	1856	8.33	
GGBS	15%		28	1	0.2430	27.68	1944	11.07	10.77
				2	0.2405	26.85	1924	10.74	
				3	0.2415	26.30	1932	10.52	
PG	45%	Blocks	14	1-I	2.8140	28.45	1930	1.23	1.16
				2-I	2.7660	24.52	1897	1.06	
				3-I	2.7840	27.29	1909	1.18	
W/B	0.15		28	1-I	2.9160	33.54	1999	1.45	1.51
				2-I	2.8860	31.92	1979	1.38	
				3-I	2.8980	39.55	1987	1.71	

Table 10.68: Mix 8 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code OPC60/GGBS20/PG20		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	60%	Cubes	14	1	0.2253	22.78	1802	9.11	9.13
				2	0.2230	22.48	1784	8.99	
				3	0.2275	23.25	1820	9.30	
GGBS	20%		28	1	0.2330	31.37	1864	12.55	12.92
				2	0.2372	33.20	1898	13.28	
				3	0.2354	32.37	1883	12.95	
PG	20%	Blocks	14	1-I	2.7036	31.69	1854	1.37	1.27
				2-I	2.6760	28.68	1835	1.24	
				3-I	2.7300	27.53	1872	1.19	
W/B	0.15		28	1-II	2.7960	39.79	1917	1.72	1.78
				2-I	2.8464	45.11	1952	1.95	
				3-I	2.8248	38.86	1937	1.68	

Table 10.69: Mix 9 - Mixture design and stress for OPC-GGBS-PG at 14 and 28 days

Mix code OPC40/GGBS45/PG15		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	40%	Cubes	14	1	0.2220	33.75	1776	13.50	13.88
				2	0.2245	35.80	1796	14.32	
				3	0.2210	34.60	1768	13.84	
GGBS	45%		28	1	0.2295	42.78	1836	17.11	17.23
				2	0.2300	41.30	1840	16.52	
				3	0.2310	45.13	1848	18.05	
PG	15%	Blocks	14	1-I	2.6640	42.79	1827	1.85	1.93
				2-I	2.6940	47.42	1847	2.05	
				3-I	2.6520	43.95	1818	1.90	
W/B	0.15		28	1-II	2.7540	52.51	1888	2.27	2.42
				2-I	2.7600	59.68	1893	2.58	
				3-I	2.7720	55.98	1901	2.42	

Table 10.70: Mix 1 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/BPD10/ ROSA20									
OPC	70%	Cubes	14	1	0.2330	68.73	1864.0	27.49	26.47
				2	0.2360	60.92	1888.0	24.37	
				3	0.2330	68.85	1864.0	27.54	
BPD	10%		28	1	0.2400	93.85	1920.0	37.54	50.37
				2	0.2415	92.98	1932.0	37.19	
				3	0.2425	97.10	1940.0	38.84	
ROSA	20%	Blocks	14	1-I	2.8802	88.29	1974.8	3.82	3.69
				2-I	2.8568	87.79	1958.8	3.79	
				3-I	2.8362	80.17	1944.7	3.47	
W/B	0.15		28	1-II	2.9788	101.17	1989.7	4.24	4.31
				2-I	2.9089	101.79	1994.5	4.43	
				3-I	2.8931	99.48	1983.7	4.30	

Table 10.71: Mix 2 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/BPD15/ ROSA25									
OPC	60%	Cubes	14	1	0.2215	43.29	1772.0	17.32	16.89
				2	0.2185	42.29	1748.0	16.92	
				3	0.2170	41.04	1736.0	16.42	
BPD	15%		28	1	0.2275	75.35	1820.0	30.14	30.25
				2	0.2290	72.04	1832.0	28.82	
				3	0.2270	79.48	1816.0	31.79	
ROSA	25%	Blocks	14	1-I	2.7682	74.79	1898.1	3.23	3.25
				2-I	2.7368	70.67	1876.5	3.06	
				3-I	2.7559	80.29	1889.6	3.47	
W/B	0.15		28	1-II	2.9649	86.41	1920.6	3.62	3.63
				2-I	2.8041	85.52	1922.7	3.69	
				3-I	2.8073	83.23	1924.9	3.59	

Table 10.72: Mix 3 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BPD20/ ROSA30									
OPC	50%	Cubes	14	1	0.2185	49.29	1748.0	19.72	18.95
				2	0.2143	45.50	1714.4	18.20	
				3	0.2166	47.32	1732.8	18.93	
BPD	20%		28	1	0.2260	78.22	1808.0	31.29	31.70
				2	0.2285	80.67	1828.0	32.27	
				3	0.2270	78.85	1816.0	31.54	
ROSA	30%	Blocks	14	1-I	2.6230	80.73	1798.5	3.49	3.45
				2-I	2.7054	81.48	1854.9	3.52	
				3-I	2.7131	77.54	1860.3	3.35	
W/B	0.15		28	1-II	2.6474	96.58	1841.7	4.05	4.12
				2-I	2.6728	97.04	1832.6	4.19	
				3-I	2.6714	95.32	1831.7	4.12	

Table 10.73: Mix 4 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BPD25/ ROSA35									
OPC	40%	Cubes	14	1	0.2180	36.92	1744.0	14.77	16.45
				2	0.2195	48.42	1752.0	18.57	
				3	0.2160	40.04	1728.0	16.02	
BPD	25%		28	1	0.2295	49.92	1832.0	19.97	19.63
				2	0.2250	48.36	1800.0	19.34	
				3	0.2273	48.92	1816.0	19.57	
ROSA	35%	Blocks	14	1-I	2.5816	68.22	1770.1	2.95	3.01
				2-I	2.6211	70.92	1797.2	3.07	
				3-I	2.6002	69.48	1782.9	3.00	
W/B	0.15		28	1-II	2.7119	77.35	1849.2	3.24	3.68
				2-I	2.6891	88.04	1843.8	3.81	
				3-I	2.6260	90.98	1800.6	3.93	

Table 10.74: Mix 5 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/BPD30/ ROSA40									
OPC	30%	Cubes	14	1	0.2083	35.22	1666.4	14.09	15.02
				2	0.2115	37.71	1692.0	15.08	
				3	0.2120	39.72	1696.0	15.89	
BPD	30%		28	1	0.2185	40.56	1748.0	16.29	17.09
				2	0.2200	42.80	1760.0	17.12	
				3	0.2225	44.62	1780.0	17.85	
ROSA	40%	Blocks	14	1-I	2.5555	36.92	1752.2	1.59	1.66
				2-I	2.5096	37.98	1720.7	1.64	
				3-I	2.5445	40.28	1744.7	1.74	
W/B	0.15		28	1-II	2.6716	61.48	1757.6	2.58	2.59
				2-I	2.5376	59.92	1739.9	2..59	
				3-I	2.5789	60.39	1768.3	2.61	

Table 10.75: Mix 6 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BPD20/ ROSA40									
OPC	40%	Cubes	14	1	0.2030	40.33	1624.0	16.13	16.92
				2	0.2050	42.40	1640.0	16.96	
				3	0.2055	44.17	1644.0	17.67	
BPD	20%		28	1	0.2160	49.10	1728.0	19.64	20.87
				2	0.2185	51.48	1748.0	20.59	
				3	0.2180	52.85	1744.0	21.14	
ROSA	40%	Blocks	14	1-I	2.7055	72.52	1855.1	3.14	3.04
				2-I	2.6895	68.01	1844.1	2.94	
				3-I	2.6920	70.66	1845.8	3.05	
W/B	0.15		28	1-III	2.6550	100.23	1863.2	4.35	4.19
				2-III	2.6535	96.35	1862.1	4.18	
				3-III	2.6500	93.48	1859.6	4.05	

Table 10.76: Mix 7 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC30/BPD10/ ROSA60									
OPC	30%	Cubes	14	1	0.2050	42.37	1640.0	16.95	16.36
				2	0.2035	40.85	1628.0	16.34	
				3	0.2030	39.50	1624.0	15.80	
BPD	10%		28	1	0.2095	48.22	1676.0	19.29	19.74
				2	0.2100	49.06	1680.0	19.62	
				3	0.2105	50.77	1684.0	20.31	
ROSA	60%	Blocks	14	1-I	2.5070	40.26	1718.9	1.74	1.85
				2-I	2.5095	42.87	1720.7	1.85	
				3-I	2.5100	45.30	1721.0	1.96	
W/B	0.15		28	1-I	2.5126	65.08	1722.8	2.81	2.91
				2-I	2.5135	67.20	1723.4	2.91	
				3-II	2.5330	69.41	1736.8	3.00	

Table 10.77: Mix8 - Mixture design and stress for OPC-ROSA-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (KN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BPD10/ ROSA40									
OPC	50%	Cubes	14	1	0.2190	78.21	1744.0	31.28	30.87
				2	0.2185	76.30	1748.0	30.52	
				3	0.2195	77.05	1756.0	30.82	
BPD	10%		28	1	0.2275	125.71	1820.0	50.28	51.36
				2	0.2280	128.83	1824.0	51.53	
				3	0.2285	130.65	1828.0	52.26	
ROSA	40%	Blocks	14	1-I	2.7202	88.13	1865.2	3.81	3.74
				2-I	2.7183	84.82	1863.8	3.67	
				3-I	2.7196	86.22	1864.7	3.73	
W/B	0.15		28	1-I	2.7630	101.78	1894.5	4.40	4.38
				2-II	2.7684	108.35	1821.3	4.54	
				3-I	2.7582	96.81	1891.2	4.19	

Table 10.78: Mix 1 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/BPD10/ GGBS20									
OPC	70 %	Cubes	14	1	0.2575	58.10	2060.0	23.24	22.09
				2	0.2545	52.82	2036.0	21.13	
				3	0.2560	54.72	2048.0	21.89	
BPD	10 %		28	1	0.2605	79.60	2084.0	31.84	30.43
				2	0.2593	75.44	2074.4	30.18	
				3	0.2584	73.20	2067.2	29.28	
GGBS	20 %	Blocks	14	1-II	3.0773	77.23	2024.5	3.34	3.38
				2-I	2.9579	81.54	2028.1	3.53	
				3-I	2.9329	75.79	2010.9	3.28	
W/B	0.15		28	1-I	2.9979	111.48	2055.6	4.82	4.55
				2-I	3.0070	106.42	2061.8	4.60	
				3-I	2.9857	98.04	2047.2	4.24	

Table 10.79: Mix 2 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/BPD10/ GGBS30									
OPC	60 %	Cubes	14	1	0.2470	55.29	1976.0	22.12	21.72
				2	0.2430	53.62	1944.0	21.45	
				3	0.2455	53.98	1964.0	21.59	
BPD	10 %		28	1	0.2520	70.82	2016.0	28.33	27.76
				2	0.2500	68.40	2000.0	27.36	
				3	0.2510	68.99	2008.0	27.59	
GGBS	30 %	Blocks	14	1-I	2.9287	73.98	2008.1	3.20	3.17
				2-I	2.9330	75.23	2011.1	3.25	
				3-I	2.9253	70.60	2005.8	3.05	
W/B	0.15		28	1-II	3.1063	88.48	2043.6	3.71	3.73
				2-I	2.9971	87.79	2055.0	3.79	
				3-I	2.9444	85.20	2018.9	3.68	

Table 10.80: Mix 3 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code OPC50/BPD7/ GGBS43		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	50 %	Cubes	14	1	0.2370	27.42	1896.0	10.97	11.98
				2	0.2375	30.05	1900.0	12.02	
				3	0.2380	32.37	1904.0	12.95	
BPD	10 %		28	1	0.2465	58.20	1972.0	23.28	21.56
				2	0.2420	50.68	1936.0	20.27	
				3	0.2445	52.84	1956.0	21.14	
GGBS	40 %	Blocks	14	1-I	2.9245	69.94	2005.2	2.93	2.91
				2-I	2.8126	65.50	1928.5	2.83	
				3-I	2.8149	68.56	1930.1	2.96	
W/B	0.15		28	1-II	2.8508	75.06	1965.5	3.24	3.28
				2-I	2.8638	76.44	1963.6	3.30	
				3-I	2.8573	76.56	1959.1	3.31	

Table 10.81: Mix 4 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code OPC50/BPD5/ GGBS45		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	50 %	Cubes	14	1	0.2365	72.85	1892.0	29.14	30.29
				2	0.2370	76.00	1896.0	30.40	
				3	0.2375	78.32	1900.0	31.33	
BPD	5 %		28	1	0.2450	99.48	1960.0	39.79	39.76
				2	0.2455	100.67	1964.0	40.27	
				3	0.2430	98.04	1944.0	39.22	
GGBS	45 %	Blocks	14	1-I	2.9245	59.17	2005.2	2.56	2.46
				2-I	2.8860	58.98	1978.8	2.55	
				3-I	2.8684	52.17	1966.8	2.26	
W/B	0.15		28	1-II	3.0873	138.73	2099.1	5.81	5.86
				2-I	3.0503	135.67	2091.5	5.87	
				3-I	3.0638	136.20	2100.7	5.89	

Table 10.82: Mix 5 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code OPC40/BPD5/ GGBS55		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	40 %	Cubes	14	1	0.2350	72.87	1880.0	29.15	28.57
				2	0.2315	70.48	1852.0	28.19	
				3	0.2330	70.96	1864.0	28.38	
BPD	5 %		28	1	0.2440	85.90	1952.0	34.36	34.62
				2	0.2445	88.23	1956.0	35.29	
				3	0.2432	85.51	1945.6	34.20	
GGBS	55 %	Blocks	14	1-I	2.9312	56.29	2009.8	2.36	2.48
				2-I	2.8268	57.42	1938.2	2.48	
				3-I	2.8478	60.33	1952.6	2.61	
W/B	0.15		28	1-II	2.8380	92.98	1937.1	4.02	3.92
				2-I	2.8223	90.50	1935.1	3.91	
				3-I	2.8158	88.73	1930.7	3.84	

Table 10.83: Mix 6 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code OPC75/BPD5/ GGBS20		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC	75 %	Cubes	14	1	0.2551	76.17	2040.8	30.47	30.94
				2	0.2523	75.80	2018.4	30.32	
				3	0.2574	80.10	2059.2	32.04	
BPD	5 %		28	1	0.2590	125.81	2072.0	50.32	48.76
				2	0.2595	119.06	2076.0	47.62	
				3	0.2595	120.88	2076.0	48.35	
GGBS	20	Blocks	14	1-I	3.1371	88.67	2150.9	3.83	3.91
				2-I	3.1609	90.85	2167.3	3.93	
				3-I	3.1690	92.02	2172.9	3.98	
W/B	0.15		28	1-II	3.2860	136.87	2188.8	5.74	5.87
				2-I	3.1880	138.63	2185.9	5.99	
				3-I	3.1805	135.92	2180.8	5.88	

Table 10.84: Mix 7 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BPD20/ GGBS30									
OPC	50 %	Cubes	14	1	0.2425	29.10	1940	11.64	11.86
				2	0.2430	30.13	1944	12.05	
				3	0.2435	29.70	1948	11.88	
BPD	20 %		28	1	0.2490	39.93	1992	15.97	16.59
				2	0.2505	42.35	2004	16.94	
				3	0.2495	42.13	1996	16.85	
GGBS	30 %	Blocks	14	1-I	2.910	35.62	1995	1.54	1.67
				2-I	2.916	42.33	1999	1.83	
				3-I	2.922	38.17	2004	1.65	
W/B	0.15		28	1-I	2.988	44.87	2049	1.94	2.23
				2-I	3.006	58.06	2061	2.51	
				3-I	2.994	51.58	2053	2.23	

Table 10.85: Mix 8 - Mixture design and stress for OPC-GGBS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BPD40/ GGBS20									
OPC	40 %	Cubes	14	1	0.2345	24.7	1884	9.88	10.44
				2	0.2370	26.9	1896	10.76	
				3	0.2365	26.73	1892	10.69	
BPD	40 %		28	1	0.2440	33.73	1952	13.49	13.69
				2	0.2460	34.18	1968	13.67	
				3	0.2465	34.80	1972	13.92	
GGBS	20 %	Blocks	14	1-I	2.826	28.22	1938	1.22	1.47
				2-I	2.844	37.01	1950	1.60	
				3-I	2.838	36.78	1946	1.59	
W/B	0.15		28	1-I	2.928	40.71	2008	1.76	1.84
				2-I	2.952	42.56	2024	1.84	
				3-I	2.958	44.64	2028	1.93	

Table 10.86: Mix 1 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC80/BPD10/ BOS10									
OPC	80 %	Cubes	14	1	0.2580	51.79	2064.0	20.72	21.13
				2	0.2600	54.29	2080.0	21.72	
				3	0.2575	52.36	2060.0	20.94	
BPD	10 %		28	1	0.2645	82.64	2116.0	33.06	33.62
				2	0.2680	90.23	2144.0	36.09	
				3	0.2650	85.42	2120.0	34.17	
BOS	10 %	Blocks	14	1-I	3.1855	69.51	2184.2	3.01	3.11
				2-I	3.1932	74.04	2189.5	3.20	
				3-I	3.1897	72.23	2187.1	3.12	
W/B	0.15		28	1-II	3.2681	86.01	2190.1	3.60	3.18
				2-I	3.2058	68.37	2198.1	2.90	
				3-I	3.2141	70.65	2203.8	3.05	

Table 10.87: Mix 2 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC70/BPD10/ BOS20									
OPC	70 %	Cubes	14	1	0.2670	80.35	2136.0	32.14	32.45
				2	0.2685	82.17	2148.0	32.87	
				3	0.2660	80.88	2128.0	32.35	
BPD	10 %		28	1	0.2710	99.67	2168.0	39.87	39.26
				2	0.2710	98.40	2168.0	39.36	
				3	0.2700	96.37	2160.0	38.55	
BOS	20 %	Blocks	14	1-I	3.2866	77.35	2253.5	3.34	3.32
				2-I	3.266.6	74.66	2239.8	3.23	
				3-I	3.2894	78.20	2255.4	3.38	
W/B	0.15		28	1-II	3.4021	88.41	2238.2	3.71	3.61
				2-I	3.323.8	84.22	2279.0	3.64	
				3-I	3.3127	80.86	2271.4	3.49	

Table 10.88: Mix 3 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC60/BPD7/BOS33									
OPC	60 %	Cubes	14	1	0.2735	86.98	2188.0	34.79	33.94
				2	0.2705	80.32	2164.0	32.13	
				3	0.2745	87.27	2196.0	34.91	
BPD	7 %		28	1	0.2820	103.72	2256.0	41.49	40.56
				2	0.2815	100.66	2252.0	40.26	
				3	0.2770	99.85	2216.0	39.94	
BOS	33 %	Blocks	14	1-I	3.2473	80.37	2226.6	3.47	3.56
				2-I	3.2789	82.60	2248.2	3.57	
				3-I	3.2497	84.48	2228.2	3.65	
W/B	0.15		28	1-II	3.3544	112.54	2296.8	4.87	4.51
				2-I	3.3440	102.2	2292.9	4.42	
				3-I	3.3503	98.00	2297.2	4.24	

Table 10.89: Mix 4 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC50/BPD5/BOS45									
OPC	50 %	Cubes	14	1	0.2825	89.36	2260.0	35.74	35.47
				2	0.2820	90.45	2256.0	36.18	
				3	0.2760	86.22	2208.0	34.49	
BPD	5 %		28	1	0.2860	101.77	2288.0	40.71	41.30
				2	0.2880	105.22	2304.0	42.09	
				3	0.2870	102.78	2296.0	41.11	
BOS	45 %	Blocks	14	1-I	3.3337	89.72	2285.8	3.88	3.66
				2-I	3.3192	77.48	2275.9	3.35	
				3-I	3.3250	86.60	2279.8	3.74	
W/B	0.15		28	1-II	3.4552	122.66	2330.2	5.14	4.79
				2-I	3.3968	108.70	2329.1	4.69	
				3-I	3.3876	105.43	2322.8	4.56	

Table 10.90: Mix 5 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BPD5/ BOS55									
OPC	40 %	Cubes	14	1	0.2880	92.27	2304.0	36.91	36.55
				2	0.2830	90.82	2264.0	36.33	
				3	0.2790	91.02	2232.0	36.41	
BPD	5 %		28	1	0.2895	115.04	2316.0	46.02	47.43
				2	0.2950	123.23	2360.0	49.29	
				3	0.2930	117.48	2344.0	46.99	
BOS	55 %	Blocks	14	1-I	3.3997	97.67	2331.1	4.22	4.04
				2-I	3.4075	88.21	2336.4	3.81	
				3-I	3.4128	94.63	2340.0	4.09	
W/B	0.15		28	1-II	3.4808	129.88	2370.0	5.44	5.16
				2-I	3.4557	118.30	2369.4	5.11	
				3-I	3.4419	113.77	2359.9	4.92	

Table 10.91: Mix 6 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BPD50/ BOS10									
OPC	40 %	Cubes	14	1	0.2530	29.75	2024	11.90	11.51
				2	0.2535	27.23	2028	10.89	
				3	0.2525	29.38	2020	11.75	
BPD	50 %		28	1	0.2620	35.70	2096	14.28	14.48
				2	0.2640	37.95	2112	15.18	
				3	0.2605	34.93	2084	13.97	
BOS	10 %	Blocks	14	1-I	3.0360	30.99	2082	1.34	1.21
				2-I	3.0420	27.76	2086	1.20	
				3-I	3.0300	24.98	2078	1.08	
W/B	0.15		28	1-II	3.1440	35.85	2156	1.55	1.52
				2-I	3.1680	30.53	2172	1.32	
				3-I	3.1260	39.32	2143	1.70	

Table 10.92: Mix 7 - Mixture design and stress for OPC-BOS-BPD at 14 and 28 days

Mix code		Type	Age (days)	No.	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Strength at failure load (MPa)	Average strength at failure load (MPa)
OPC40/BPD20/ BOS40									
OPC	40 %	Cubes	14	1	0.2800	47.75	2240	19.10	18.45
				2	0.2805	44.70	2244	17.88	
				3	0.2775	45.90	2220	18.36	
BPD	20 %		28	1	0.2850	52.60	2280	21.04	21.23
				2	0.2865	51.90	2292	20.76	
				3	0.2820	54.70	2256	21.88	
BOS	40%	Blocks	14	1-I	3.3600	42.56	2304	1.84	1.94
				2-I	3.3660	45.57	2308	1.97	
				3-I	3.3300	46.73	2283	2.02	
W/B	0.15		28	1-II	3.4200	49.73	2345	2.15	2.21
				2-I	3.4380	47.88	2357	2.07	
				3-I	3.3840	55.52	2320	2.40	

Table 10.93: Ratio between compressive to split tensile strength at 28 days

Mix code	Compressive strength (MPa)	Split tensile strength (MPa)	Ratio between compressive to split tensile strength	Average of the ratios
OPC70/ROSA30	24.21	4.25	5.7	
OPC60/ROSA40	24.94	5.22	4.8	
OPC50/ROSA50	26.38	5.42	4.9	5.5
OPC40/ROSA60	23.24	3.72	6.2	
OPC30/ROSA70	16.82	2.90	5.8	
OPC40/GGBS30/BOS30	23.24	4.30	5.4	
OPC30/GGBS40/BOS30	25.48	4.45	5.7	
OPC30/GGBS30/BOS40	34.75	5.39	6.4	
OPC30/GGBS35/BOS35	34.36	4.38	7.8	6.6
OPC20/GGBS40/BOS40	31.43	4.09	7.7	
OPC20/GGBS30/BOS50	35.11	5.41	6.5	
OPC70/BOS25/PG5	34.41	4.44	7.8	
OPC60/BOS35/PG5	40.76	5.09	8.0	
OPC50/BOS45/PG5	37.63	4.89	7.7	
OPC50/BOS47/PG3	37.35	4.77	7.8	
OPC50/BOS30/PG20	15.11	1.93	7.8	7.9
OPC40/BOS55/PG5	37.35	4.57	8.2	
OPC30/BOS65/PG5	33.29	4.04	8.2	
OPC30/BOS25/PG45	17.49	2.21	7.9	
OPC30/BOS55/PG15	11.13	1.40	7.9	
OPC30/ROSA35/BOS35	25.14	4.13	6.1	
OPC40/ROSA30/BOS30	34.79	4.60	7.6	
OPC50/ROSA25/BOS25	34.81	4.79	7.3	7.6
OPC50/ROSA20/BOS30	34.57	4.65	7.4	
OPC52/ROSA30/BOS18	41.80	5.14	8.1	
OPC60/ROSA20/BOS20	41.11	4.94	8.3	
OPC70/ROSA15/BOS15	37.95	4.67	8.1	

Table 10.94: Ratio between compressive to split tensile strength at 28 days

Mix code	Compressive strength (MPa)	Split tensile strength (MPa)	Ratio between compressive to split tensile strength	Average of the ratios
OPC40/ROSA55/PG5	15.02	2.23	6.7	
OPC50/ROSA45/PG5	21.22	2.68	7.9	
OPC60/ROSA35/PG5	22.82	3.22	7.1	
OPC70/ROSA25/PG5	24.77	3.51	7.1	
OPC70/ROSA27/PG3	28.90	3.74	7.7	7.5
OPC80/ROSA15/PG5	30.78	3.90	7.8	
OPC80/ROSA17/PG3	32.11	4.03	7.9	
OPC70/BOS30	48.13	4.92	9.8	
OPC60/BOS40	55.68	5.32	10.5	
OPC50/BOS50	49.57	5.18	9.6	9.6
OPC40/BOS60	45.60	5.16	8.8	
OPC30/BOS70	40.48	4.43	9.1	
OPC80/GGBS15/PG5	22.19	3.29	6.7	
OPC70/GGBS25/PG5	30.72	4.49	6.8	
OPC60/GGBS35/PG5	27.39	3.71	7.4	7.2
OPC60/GGBS20/PG20	12.92	1.78	7.3	
OPC50/GGBS45/PG5	24.76	3.37	7.3	
OPC50/GGBS47/PG3	26.39	3.39	7.8	
OPC40/GGBS55/PG5	22.85	3.32	6.9	
OPC40/GGBS15/PG45	10.77	1.51	7.1	
OPC40/GGBS45/PG15	17.23	2.42	7.1	
OPC70/ROSA20/BPD10	50.37	4.31	11.7	
OPC60/ROSA25/BPD15	30.25	3.63	8.3	
OPC50/ROSA30/BPD20	31.70	4.12	7.7	
OPC50/ROSA40/BPD10	51.36	4.38	11.7	7.8
OPC40/ROSA35/BPD25	19.63	3.68	5.3	
OPC40/ROSA40/BPD20	20.87	4.19	4.9	
OPC30/ROSA40/BPD30	19.74	2.91	6.8	
OPC30/ROSA60/BPD10	17.09	2.59	6.6	
OPC75/GGBS20/BPD5	48.76	5.87	8.3	
OPC70/GGBS20/BPD10	30.43	4.55	6.7	
OPC60/GGBS30/BPD10	27.76	3.73	7.4	
OPC50/GGBS40/BPD10	39.76	5.86	6.8	
OPC50/GGBS45/BPD5	21.56	3.28	6.6	
OPC50/GGBS30/BPD20	16.59	2.23	7.4	7.4
OPC40/GGBS55/BPD5	13.69	1.84	7.4	
OPC40/GGBS20/BPD40	34.62	3.92	8.8	
OPC80/BOS10/BPD10	33.62	3.18	10.6	
OPC70/BOS20/BPD10	39.26	3.61	10.9	
OPC60/BOS33/BPD7	40.56	4.51	8.9	
OPC50/BOS45/BPD5	41.30	4.79	8.6	
OPC40/BOS55/BPD5	47.43	5.16	9.2	9.6
OPC40/BOS10/BPD50	14.48	1.52	9.5	
OPC40/BOS40/BPD20	21.23	2.21	9.6	

10.4 Results of mixes in the second phase

Table 10.95: Mixture design and strength results for OPC10-GGBS4 at 14 and 28 days – Factory control Mix I

<table>
<tr><td colspan="2">Mix code</td><td colspan="6">Factory control Mix I</td></tr>
<tr><td colspan="3">Cement</td><td>GGBS</td><td>4mm-Dust</td><td colspan="2">6mm Clean</td><td>Sand</td></tr>
<tr><td colspan="3">10%</td><td>4%</td><td>53%</td><td colspan="2">9%</td><td>24%</td></tr>
<tr><td rowspan="10">Cubes</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Compressive strength (MPa)</td><td>Mean compressive strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="4">14</td><td>0.2740</td><td>30.8</td><td>2192.0</td><td>12.3</td><td rowspan="4">11.7</td></tr>
<tr><td>2</td><td>0.2735</td><td>29.7</td><td>2188.0</td><td>11.9</td></tr>
<tr><td>3</td><td>0.2735</td><td>28.5</td><td>2188.0</td><td>11.4</td></tr>
<tr><td>4</td><td>0.2730</td><td>27.2</td><td>2184.0</td><td>10.9</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>0.2905</td><td>45.1</td><td>2324.0</td><td>18.0</td><td rowspan="5">18.6</td></tr>
<tr><td>2</td><td>0.2910</td><td>46.3</td><td>2328.0</td><td>18.5</td></tr>
<tr><td>3</td><td>0.2915</td><td>47.5</td><td>2332.0</td><td>19.0</td></tr>
<tr><td>4</td><td>0.2900</td><td>40.9</td><td>2320.0</td><td>16.4</td></tr>
<tr><td>5</td><td>0.2920</td><td>47.5</td><td>2336.0</td><td>19.0</td></tr>
<tr><td rowspan="9">Blocks</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Split tensile strength (MPa)</td><td>Mean split tensile strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>3.4670</td><td>47.3</td><td>2377.2</td><td>2.1</td><td rowspan="3">2.0</td></tr>
<tr><td>2</td><td>3.4665</td><td>45.7</td><td>2376.9</td><td>1.9</td></tr>
<tr><td>3</td><td>3.4655</td><td>43.9</td><td>2376.2</td><td>1.9</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>3.4770</td><td>74.6</td><td>2384.1</td><td>3.2</td><td rowspan="5">3.2</td></tr>
<tr><td>2</td><td>3.4845</td><td>75.9</td><td>2389.2</td><td>3.3</td></tr>
<tr><td>3</td><td>3.4740</td><td>72.4</td><td>2381.9</td><td>3.1</td></tr>
<tr><td>4</td><td>3.4705</td><td>70.1</td><td>2379.6</td><td>3.0</td></tr>
<tr><td>5</td><td>3.4745</td><td>73.2</td><td>2382.3</td><td>3.2</td></tr>
</table>

Table 10.96: Mixture design and strength results for OPC10-PFA4 at 14 and 28 days – Factory control Mix II

<table>
<tr><td colspan="2">Mix code</td><td colspan="6">Factory control Mix II</td></tr>
<tr><td colspan="3">Cement</td><td>PFA</td><td>4mm-Dust</td><td colspan="2">6mm Clean</td><td>Sand</td></tr>
<tr><td colspan="3">10%</td><td>4%</td><td>53%</td><td colspan="2">9%</td><td>24%</td></tr>
<tr><td rowspan="7">Cubes</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Compressive strength (MPa)</td><td>Mean compressive strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>0.2835</td><td>30.2</td><td>2268.0</td><td>12.1</td><td rowspan="3">12.9</td></tr>
<tr><td>2</td><td>0.2850</td><td>32.8</td><td>2280.0</td><td>13.1</td></tr>
<tr><td>3</td><td>0.2845</td><td>31.6</td><td>2276.0</td><td>12.6</td></tr>
<tr><td>1</td><td rowspan="3">28</td><td>0.2905</td><td>42.3</td><td>2324.0</td><td>16.9</td><td rowspan="3">15.7</td></tr>
<tr><td>2</td><td>0.2890</td><td>38.8</td><td>2312.0</td><td>15.5</td></tr>
<tr><td>3</td><td>0.2895</td><td>39.5</td><td>2316.0</td><td>15.8</td></tr>
<tr><td rowspan="9">Blocks</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Split tensile strength (MPa)</td><td>Mean split tensile strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>3.4790</td><td>44.7</td><td>2385.4</td><td>1.9</td><td rowspan="3">2.0</td></tr>
<tr><td>2</td><td>3.4805</td><td>46.9</td><td>2386.5</td><td>2.0</td></tr>
<tr><td>3</td><td>3.4875</td><td>48.7</td><td>2391.3</td><td>2.1</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>3.4930</td><td>58.4</td><td>2395.0</td><td>2.5</td><td rowspan="5">2.6</td></tr>
<tr><td>2</td><td>3.4935</td><td>60.3</td><td>2395.4</td><td>2.6</td></tr>
<tr><td>3</td><td>3.5190</td><td>62.3</td><td>2412.8</td><td>2.7</td></tr>
<tr><td>4</td><td>3.4950</td><td>60.6</td><td>2396.4</td><td>2.6</td></tr>
<tr><td>5</td><td>3.5010</td><td>61.8</td><td>2400.5</td><td>2.7</td></tr>
</table>

Table 10.97: Mixture design and strength results for OPC2.8-GGBS4.2-BOS7 at 14 and 28 days

Mix code		OPC20/GGBS30/BOS50				Mix No	1
Cement		GGBS	BOS	4mm-Dust	6mm Clean		Sand
2.8%		4.2%	7%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2865	23.5	2292.0	9.4	9.5
	2		0.2870	23.8	2296.0	9.5	
	3		0.2885	24.0	2308.0	9.6	
	4		0.2875	23.8	2300.0	9.5	
	1	28	0.3010	29.7	2408.0	11.9	12.6
	2		0.3025	32.5	2420.0	13.0	
	3		0.3020	31.8	2416.0	12.7	
	4		0.3015	30.5	2412.0	12.2	
	5		0.3015	29.3	2412.0	11.7	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4480	33.3	2364.2	1.4	1.5
	2		3.4500	34.7	2365.6	1.5	
	3		3.4500	34.2	2365.6	1.5	
	1	28	3.4950	46.7	2396.5	2.0	1.9
	2		3.4925	43.4	2394.7	1.9	
	3		3.4920	44.8	2394.4	1.9	
	4		3.4930	45.2	2395.1	1.9	
	5		3.4915	41.4	2394.1	1.8	

Table 10.98: Mixture design and strength results for OPC8.4-BOS4.9-PG0.7 at 14 and 28 days

Mix code		OPC60/BOS35/PG5				Mix No	2
Cement		BOS	PG	4mm-Dust	6mm Clean		Sand
8.4%		4.9%	0.7%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2920	14.2	2336.0	5.7	6.0
	2		0.2935	14.8	2348.0	5.9	
	3		0.2940	15.3	2352.0	6.1	
	4		0.2930	15.0	2344.0	6.0	
	1	28	0.3080	16.2	2464.0	6.5	6.7
	2		0.3115	18.7	2492.0	7.5	
	3		0.3106	17.4	2484.8	6.9	
	4		0.3103	17.0	2482.4	6.8	
	5		0.3112	18.5	2489.6	7.4	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.5695	18.9	2447.5	0.8	0.8
	2		3.5680	18.0	2446.5	0.8	
	3		3.5720	19.2	2449.3	0.8	
	1	28	3.5850	26.3	2458.2	1.1	1.1
	2		3.5830	23.8	2456.8	1.0	
	3		3.5835	24.4	2457.1	1.1	
	4		3.5840	24.5	2457.5	1.1	
	5		3.5845	24.7	2457.8	1.1	

Table 10.99: Mixture design and strength results for OPC7.3-ROSA4.2-BOS2.5 at 14 and 28 days

Mix code		OPC52/ROSA30/BOS18				Mix No	3
Cement		ROSA	BOS	4mm-Dust	6mm Clean		Sand
7.3%		4.2%	2.5%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2820	23.6	2256.0	9.4	9.4
	2		0.2815	21.7	2252.0	8.7	
	3		0.2820	24.3	2256.0	9.7	
	4		0.2810	22.7	2248.0	9.1	
	1	28	0.2920	30.0	2336.0	12.0	11.8
	2		0.2925	30.2	2340.0	12.1	
	3		0.2920	29.0	2336.0	11.6	
	4		0.2925	28.9	2340.0	11.6	
	5		0.2920	27.8	2336.0	11.1	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4510	34.7	2366.3	1.5	1.5
	2		3.4520	35.4	2366.9	1.5	
	3		3.4525	36.2	2367.3	1.6	
	1	28	3.4760	52.6	2383.4	2.3	2.2
	2		3.4700	48.9	2379.3	2.1	
	3		3.4725	50.0	2381.0	2.2	
	4		3.4725	51.2	2381.0	2.2	
	5		3.4720	44.9	2380.7	1.9	

Table 10.100: Mixture design and strength results for OPC5.6-BPD0.7-BOS7.7 at 14 and 28 days

Mix code		OPC40/BPD5/BOS55					Mix No	4
Cement		BPD	BOS	4mm-Dust	6mm Clean			Sand
5.6%		0.7%	7.7%	53%	9%			24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)		Mean compressive strength (MPa)
	1	14	0.2925	16.5	2340.0	6.6		6.6
	2		0.2925	16.9	2340.0	6.8		
	3		0.2920	15.8	2336.0	6.3		
	4		0.2925	16.3	2340.0	6.5		
	1	28	0.3150	21.3	2520.0	8.5		8.7
	2		0.3155	21.7	2524.0	8.7		
	3		0.3160	22.8	2528.0	9.1		
	4		0.3150	22.3	2520.0	8.9		
	5		0.3155	21.9	2524.0	8.8		
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)		Mean split tensile strength (MPa)
	1	14	3.5300	18.3	2420.5	0.8		0.9
	2		3.5355	20.5	2424.2	0.9		
	3		3.5335	20.2	2422.9	0.9		
	1	28	3.5550	33.9	2437.6	1.5		1.5
	2		3.5560	35.8	2438.3	1.5		
	3		3.5545	31.2	2437.3	1.3		
	4		3.5555	35.2	2437.9	1.5		
	5		3.5560	36.3	2438.3	1.6		

Table 10.101: Mixture design and strength results for OPC8.4-BOS5.6 at 14 and 28 days

Mix code		OPC60/BOS40				Mix No	5
Cement		BOS	4mm-Dust	6mm Clean			Sand
8.4%		5.6%	53%	9%			24%
	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
Cubes	1	14	0.2900	13.0	2320.0	5.2	5.7
	2		0.2905	13.9	2324.0	5.6	
	3		0.2910	14.2	2328.0	5.7	
	4		0.2905	14.5	2324.0	5.8	
	1	28	0.3015	17.0	2412.0	6.8	7.5
	2		0.3025	18.4	2420.0	7.4	
	3		0.3025	19.0	2420.0	7.6	
	4		0.3020	18.2	2416.0	7.3	
	5		0.3025	19.4	2420.0	7.8	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.5525	27.5	2435.9	1.2	1.2
	2		3.5500	26.7	2434.2	1.2	
	3		3.5505	29.0	2434.5	1.3	
	1	28	3.5715	35.4	2448.9	1.5	1.6
	2		3.5760	39.9	2452.0	1.7	
	3		3.5750	37.5	2451.3	1.6	
	4		3.5735	36.8	2450.3	1.6	
	5		3.5750	37.2	2451.3	1.6	

Table 10.102: Mixture design and strength results for OPC7-ROSA7 at 14 and 28 days

<table>
<tr><td colspan="2">Mix code</td><td colspan="5">OPC50/ROSA50</td><td>Mix No</td><td>6</td></tr>
<tr><td colspan="2">Cement</td><td colspan="2">ROSA</td><td>4mm-Dust</td><td colspan="2">6mm Clean</td><td colspan="2">Sand</td></tr>
<tr><td colspan="2">7%</td><td colspan="2">7%</td><td>53%</td><td colspan="2">9%</td><td colspan="2">24%</td></tr>
<tr><td rowspan="10">Cubes</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Compressive strength (MPa)</td><td colspan="2">Mean compressive strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="4">14</td><td>0.2820</td><td>20.6</td><td>2256.0</td><td>8.2</td><td colspan="2" rowspan="4">8.3</td></tr>
<tr><td>2</td><td>0.2830</td><td>21.0</td><td>2264.0</td><td>8.4</td></tr>
<tr><td>3</td><td>0.2840</td><td>22.9</td><td>2272.0</td><td>9.2</td></tr>
<tr><td>4</td><td>0.2835</td><td>20.8</td><td>2268.0</td><td>8.3</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>0.2990</td><td>31.6</td><td>2392.0</td><td>12.6</td><td colspan="2" rowspan="5">12.2</td></tr>
<tr><td>2</td><td>0.2985</td><td>30.4</td><td>2388.0</td><td>12.2</td></tr>
<tr><td>3</td><td>0.2985</td><td>29.8</td><td>2388.0</td><td>11.9</td></tr>
<tr><td>4</td><td>0.2970</td><td>27.5</td><td>2376.0</td><td>11.0</td></tr>
<tr><td>5</td><td>0.2965</td><td>27.0</td><td>2372.0</td><td>10.8</td></tr>
<tr><td rowspan="9">Blocks</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Split tensile strength (MPa)</td><td colspan="2">Mean split tensile strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>3.5505</td><td>23.7</td><td>2434.5</td><td>1.0</td><td colspan="2" rowspan="3">1.0</td></tr>
<tr><td>2</td><td>3.5510</td><td>24.2</td><td>2434.9</td><td>1.0</td></tr>
<tr><td>3</td><td>3.5520</td><td>24.9</td><td>2435.5</td><td>1.1</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>3.5700</td><td>44.6</td><td>2447.9</td><td>1.9</td><td colspan="2" rowspan="5">2.0</td></tr>
<tr><td>2</td><td>3.5735</td><td>47.9</td><td>2450.3</td><td>2.1</td></tr>
<tr><td>3</td><td>3.5725</td><td>45.8</td><td>2449.6</td><td>1.9</td></tr>
<tr><td>4</td><td>3.5730</td><td>46.5</td><td>2449.9</td><td>2.0</td></tr>
<tr><td>5</td><td>3.5720</td><td>45.2</td><td>2449.3</td><td>1.9</td></tr>
</table>

Table 10.103: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Best mix with factory sand)

Mix code		OPC50/BPD5/GGBS45				Mix No	7
Cement		BPD	GGBS	4mm-Dust	6mm Clean		Sand
7%		0.7%	6.3%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2850	35.9	2280.0	14.4	13.5
	2		0.2845	34.7	2276.0	13.9	
	3		0.2840	33.1	2272.0	13.2	
	4		0.2840	33.8	2272.0	13.5	
	1	28	0.2950	48.4	2360.0	19.4	20.3
	2		0.2955	49.6	2364.0	19.8	
	3		0.2945	41.2	2356.0	16.5	
	4		0.2960	50.8	2368.0	20.3	
	5		0.2970	52.0	2376.0	20.8	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4875	63.0	2391.3	2.7	2.7
	2		3.4875	65.2	2391.3	2.8	
	3		3.4860	62.4	2390.2	2.7	
	1	28	3.5055	81.8	2403.6	3.5	3.6
	2		3.5100	85.4	2406.7	3.7	
	3		3.5085	82.3	2405.7	3.6	
	4		3.5120	89.2	2408.1	3.9	
	5		3.4990	76.8	2399.1	3.3	

Table 10.104: Ratio between compressive to split tensile strength at 28 days

Mix code	Compressive strength (MPa)	Split tensile strength (MPa)	Ratio between compressive to split tensile strength	Average of the ratios
OPC2.8-GGBS4.2-BOS7.0	12.6	1.9	6.6	5.7
OPC8.4-BOS4.9-PG0.7	6.7	1.1	6.1	
OPC7.3-ROSA4.2-BOS2.5	11.8	2.2	5.4	
OPC5.6-BOS7.7-BPD0.7	8.7	1.5	5.8	
OPC8.4-BOS5.6	7.5	1.6	4.7	
OPC7.0-ROSA7.0	12.2	2.0	6.1	
OPC7.0-GGBS6.3-BPD0.7	20.3	3.6	5.5	

10.5 Results of mixes in the third phase

Table 10.105: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 6mm and 4mm Bottom ash)

<table>
<tr><td colspan="2">Mix code</td><td colspan="4">OPC50/BPD5/GGBS45</td><td>Mix No</td><td>8</td></tr>
<tr><td colspan="2">Cement</td><td>BPD</td><td>GGBS</td><td>4mm-Dust (Bottom ash)</td><td colspan="2">6mm Clean (Bottom ash)</td><td>Sand</td></tr>
<tr><td colspan="2">7%</td><td>0.7%</td><td>6.3%</td><td>53%</td><td colspan="2">9%</td><td>24%</td></tr>
<tr><td rowspan="10">Cubes</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Compressive strength (MPa)</td><td>Mean compressive strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="4">14</td><td>0.2710</td><td>18.6</td><td>2168.0</td><td>7.4</td><td rowspan="4">7.4</td></tr>
<tr><td>2</td><td>0.2715</td><td>19.2</td><td>2172.0</td><td>7.7</td></tr>
<tr><td>3</td><td>0.2705</td><td>16.9</td><td>2160.0</td><td>6.8</td></tr>
<tr><td>4</td><td>0.2705</td><td>17.7</td><td>2164.0</td><td>7.1</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>0.2860</td><td>35.4</td><td>2288.0</td><td>14.2</td><td rowspan="5">13.6</td></tr>
<tr><td>2</td><td>0.2845</td><td>33.7</td><td>2276.0</td><td>13.5</td></tr>
<tr><td>3</td><td>0.2835</td><td>28.9</td><td>2268.0</td><td>11.6</td></tr>
<tr><td>4</td><td>0.2850</td><td>32.6</td><td>2280.0</td><td>13.0</td></tr>
<tr><td>5</td><td>0.2840</td><td>29.7</td><td>2272.0</td><td>11.9</td></tr>
<tr><td rowspan="9">Blocks</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Split tensile strength (MPa)</td><td>Mean split tensile strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>3.2708</td><td>34.8</td><td>2242.7</td><td>1.5</td><td rowspan="3">1.5</td></tr>
<tr><td>2</td><td>3.2775</td><td>36.5</td><td>2247.3</td><td>1.6</td></tr>
<tr><td>3</td><td>3.2690</td><td>33.0</td><td>2241.4</td><td>1.4</td></tr>
<tr><td>1</td><td rowspan="5">28</td><td>3.2949</td><td>44.7</td><td>2259.2</td><td>1.9</td><td rowspan="5">1.9</td></tr>
<tr><td>2</td><td>3.2965</td><td>46.2</td><td>2260.3</td><td>2.0</td></tr>
<tr><td>3</td><td>3.2880</td><td>43.4</td><td>2254.5</td><td>1.9</td></tr>
<tr><td>4</td><td>3.2897</td><td>44.1</td><td>2255.6</td><td>1.9</td></tr>
<tr><td>5</td><td>3.2952</td><td>45.3</td><td>2259.4</td><td>1.9</td></tr>
</table>

Table 10.106: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 4mm Bottom ash)

Mix code		OPC50/BPD5/GGBS45				Mix No	9
Cement		BPD	GGBS	4mm-Dust (Bottom ash)	6mm Clean		Sand
7%		0.7%	6.3%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2752	19.8	2201.6	7.9	7.6
	2		0.2746	18.6	2196.8	7.4	
	3		0.2748	17.2	2278.4	6.9	
	4		0.2760	18.9	2208.0	7.6	
	1	28	0.2883	30.9	2306.4	12.4	12.7
	2		0.2875	29.6	2300.0	11.8	
	3		0.2870	29.1	2296.0	11.6	
	4		0.2891	32.4	2312.8	12.9	
	5		0.2888	31.7	2310.4	12.7	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.3605	35.1	2304.2	1.5	1.6
	2		3.3680	38.9	2309.3	1.7	
	3		3.3654	37.2	2307.5	1.6	
	1	28	3.3789	51.5	2316.8	2.2	2.3
	2		3.3822	57.7	2319.1	2.5	
	3		3.3781	50.3	2316.2	2.2	
	4		3.3769	49.8	2315.4	2.2	
	5		3.3795	52.9	2317.2	2.3	

Table 10.107: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 6mm Bottom ash)

Mix code		OPC50/BPD5/GGBS45				Mix No	10
Cement		BPD	GGBS	4mm-Dust	6mm Clean (Bottom ash)		Sand
7%		0.7%	6.3%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2800	30.7	2240.0	12.3	12.6
	2		0.2815	32.6	2252.0	13.0	
	3		0.2795	29.6	2236.0	11.8	
	4		0.2805	31.5	2244.0	12.6	
	1	28	0.2875	42.5	2300.0	17.0	16.6
	2		0.2875	41.8	2300.0	16.7	
	3		0.2845	38.6	2276.0	15.4	
	4		0.2850	40.1	2280.0	16.0	
	5		0.2840	36.2	2272.0	14.5	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4550	44.8	2368.9	1.9	2.0
	2		3.4595	46.1	2372.1	2.0	
	3		3.4600	47.3	2372.4	2.0	
	1	28	3.4790	76.7	2385.4	3.3	3.2
	2		3.4750	71.4	2382.7	3.1	
	3		3.4790	75.8	2385.4	3.3	
	4		3.4790	74.4	2385.4	3.2	
	5		3.4810	82.8	2386.8	3.6	

Table 10.108: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 6mm RCA type I)

Mix code		OPC50/BPD5/GGBS45				Mix No	11
Cement		BPD	GGBS	4mm-Dust	6mm Clean (RCA type I)		Sand
7%		0.7%	6.3%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2830	32.7	2264.0	13.1	13.3
	2		0.2840	33.9	2272.0	13.6	
	3		0.2835	33.2	2268.0	13.3	
	4		0.2825	30.8	2260.0	12.3	
	1	28	0.2915	43.1	2332.0	17.2	16.9
	2		0.2910	42.7	2328.0	17.1	
	3		0.2905	40.7	2324.0	16.3	
	4		0.2900	39.9	2320.0	15.9	
	5		0.2895	38.5	2316.0	15.4	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4770	55.6	2384.1	2.4	2.4
	2		3.4795	57.1	2385.8	2.5	
	3		3.4760	53.9	2383.4	2.3	
	1	28	3.4775	73.4	2384.4	3.2	3.3
	2		3.4995	77.0	2399.5	3.3	
	3		3.4980	75.4	2398.4	3.3	
	4		3.5015	78.8	2400.9	3.4	
	5		3.5053	80.1	2403.5	3.5	

Table 10.109: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 6mm RCA type II)

Mix code		OPC50/BPD5/GGBS45				Mix No	12
Cement		BPD	GGBS	4mm-Dust	6mm Clean (RCA II)		Sand
7%		0.7%	6.3%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2825	31.6	2260.0	12.6	12.5
	2		0.2820	30.9	2256.0	12.4	
	3		0.2835	32.4	2268.0	12.9	
	4		0.2815	29.7	2252.0	11.9	
	1	28	0.2895	39.2	2316.0	15.7	15.8
	2		0.2885	37.9	2308.0	15.2	
	3		0.2885	40.0	2308.0	16.0	
	4		0.2910	42.7	2328.0	17.1	
	5		0.2900	40.2	2320.0	16.1	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4755	52.9	2383.0	2.3	2.3
	2		3.4760	53.7	2383.4	2.3	
	3		3.4770	55.2	2384.1	2.4	
	1	28	3.4930	80.9	2395.0	3.5	3.2
	2		3.4930	77.3	2395.0	3.3	
	3		3.4875	72.4	2391.3	3.1	
	4		3.4880	75.8	2391.6	3.3	
	5		3.4850	69.5	2389.5	3.0	

Table 10.110: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 4mm Recycle Glass)

Mix code		OPC50/BPD5/GGBS45				Mix No	13
Cement		BPD	GGBS	4mm (Recycled Glass)	6mm Clean		Sand
7%		0.7%	6.3%	53%	9%		24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2620	15.3	2096.0	6.1	5.5
	2		0.2615	14.0	2092.0	5.6	
	3		0.2610	13.7	2088.0	5.5	
	4		0.2610	13.2	2088.0	5.3	
	1	28	0.2735	24.8	2188.0	9.9	9.5
	2		0.2735	23.2	2188.0	9.3	
	3		0.2740	26.5	2192.0	10.6	
	4		0.2745	25.7	2196.0	10.3	
	5		0.2735	23.3	2188.0	9.3	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.3105	27.9	2269.9	1.2	1.2
	2		3.3128	28.6	2271.5	1.2	
	3		3.3170	30.5	2274.3	1.3	
	1	28	3.3393	60.4	2289.6	2.6	2.2
	2		3.3235	47.7	2278.8	2.1	
	3		3.3318	51.4	2284.5	2.2	
	4		3.3262	49.8	2280.7	2.2	
	5		3.3307	50.2	2283.7	2.2	

Table 10.111: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 6mm Recycle bricks)

Mix code		OPC50/BPD5/GGBS45					Mix No	14
Cement		BPD	GGBS	4mm-Dust	6mm Clean (Recycled bricks as aggregates)		Sand	
7%		0.7%	6.3%	53%	9%		24%	
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)	
	1	14	0.2800	20.9	2240.0	8.4	8.5	
	2		0.2810	22.3	2248.0	8.9		
	3		0.2805	21.0	2244.0	8.4		
	4		0.2820	23.8	2256.0	9.5		
	1	28	0.2930	39.7	2344.0	15.9	15.9	
	2		0.2935	40.1	2348.0	16.0		
	3		0.2935	40.9	2348.0	16.4		
	4		0.2910	35.8	2328.0	14.3		
	5		0.2925	38.6	2340.0	15.4		
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)	
	1	14	3.4905	43.2	2393.3	1.9	1.9	
	2		3.4890	41.8	2392.3	1.8		
	3		3.4910	45.4	2393.7	1.9		
	1	28	3.5165	72.0	2411.1	3.1	3.1	
	2		3.5140	70.9	2409.4	3.1		
	3		3.5135	69.8	2409.1	3.0		
	4		3.5105	63.8	2407.0	2.8		
	5		3.5120	62.0	2408.1	2.7		

Table 10.112: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 1.5 % steel fibre)

Mix code		OPC50/BPD5/GGBS45				Mix No	15
Cement		BPD	GGBS	4mm-Dust	6mm Clean	Steel Fibre	Sand
7%		0.7%	6.3%	53%	9%	1.5 %	24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2890	36.7	2312.0	14.7	14.2
	2		0.2885	35.5	2308.0	14.2	
	3		0.2875	32.0	2300.0	12.8	
	4		0.2880	34.1	2304.0	13.6	
	1	28	0.2920	37.0	2336.0	14.8	17.7
	2		0.2925	39.6	2340.0	15.8	
	3		0.2935	46.1	2348.0	18.4	
	4		0.2930	43.5	2344.0	17.4	
	5		0.2930	42.9	2344.0	17.2	
Blocks	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.5345	77.2	2423.5	3.3	3.2
	2		3.5300	69.0	2420.4	3.0	
	3		3.5325	74.6	2422.1	3.2	
	1	28	3.5480	81.9	2432.7	3.5	3.6
	2		3.5470	77.7	2432.1	3.4	
	3		3.5600	84.9	2440.9	3.7	
	4		3.5520	81.5	2435.5	3.5	
	5		3.5625	88.1	2442.7	3.8	

Table 10.113: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 6 PVA)

<table>
<tr><td colspan="2">Mix code</td><td colspan="4">OPC50/BPD5/GGBS45</td><td>Mix No</td><td>16</td></tr>
<tr><td colspan="2">Cement</td><td>BPD</td><td>GGBS</td><td>4mm-Dust</td><td>6mm Clean</td><td>PVA (Kg/m^3)</td><td>Sand</td></tr>
<tr><td colspan="2">7%</td><td>0.7%</td><td>6.3%</td><td>53%</td><td>9%</td><td>6</td><td>24%</td></tr>
<tr><td rowspan="7">Cubes</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Compressive strength (MPa)</td><td>Mean compressive strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>0.2890</td><td>33.5</td><td>2312.0</td><td>13.4</td><td rowspan="3">14.4</td></tr>
<tr><td>2</td><td>0.2900</td><td>38.4</td><td>2320.0</td><td>15.4</td></tr>
<tr><td>3</td><td>0.2900</td><td>25.1</td><td>2320.0</td><td>10.1</td></tr>
<tr><td>1</td><td rowspan="3">28</td><td>0.2915</td><td>40.5</td><td>2332.0</td><td>16.2</td><td rowspan="3">19.1</td></tr>
<tr><td>2</td><td>0.2920</td><td>49.7</td><td>2336.0</td><td>19.9</td></tr>
<tr><td>3</td><td>0.2915</td><td>45.7</td><td>2332.0</td><td>18.3</td></tr>
<tr><td rowspan="8">Blocks</td><td>No</td><td>Age (days)</td><td>Mass (kg)</td><td>Failure load (kN)</td><td>Density (kg/m^3)</td><td>Split tensile strength (MPa)</td><td>Mean split tensile strength (MPa)</td></tr>
<tr><td>1</td><td rowspan="3">14</td><td>3.4505</td><td>40.2</td><td>2365.9</td><td>1.7</td><td rowspan="3">1.7</td></tr>
<tr><td>2</td><td>3.4525</td><td>40.7</td><td>2367.3</td><td>1.8</td></tr>
<tr><td>3</td><td>3.4550</td><td>37.7</td><td>2368.9</td><td>1.6</td></tr>
<tr><td>1</td><td rowspan="4">28</td><td>3.4640</td><td>47.2</td><td>2375.1</td><td>2.0</td><td rowspan="4">2.0</td></tr>
<tr><td>2</td><td>3.4660</td><td>48.1</td><td>2376.5</td><td>2.1</td></tr>
<tr><td>3</td><td>3.4605</td><td>46.7</td><td>2372.7</td><td>2.0</td></tr>
<tr><td>4</td><td>3.4590</td><td>41.7</td><td>2371.7</td><td>1.8</td></tr>
</table>

Table 10.114: Mixture design and strength results for OPC7-BPD0.7-GGBS6.3 at 14 and 28 days (Using 10 PVA)

Mix code		OPC50/BPD5/GGBS45				Mix No	17
Cement		BPD	GGBS	4mm-Dust	6mm Clean	PVA (Kg/m^3)	Sand
7%		0.7%	6.3%	53%	9%	10	24%
Cubes	No	Age (days)	Mass (kg)	Failure load (kN)	Density (kg/m^3)	Compressive strength (MPa)	Mean compressive strength (MPa)
	1	14	0.2900	32.0	2320.0	12.8	13.4
	2		0.2905	35.0	2324.0	14.0	
	3		0.2900	24.8	2320.0	9.9	
	1	28	0.2915	33.4	2332.0	13.4	14.4
	2		0.2920	37.2	2336.0	14.9	
	3		0.2920	37.0	2336.0	14.8	
Blocks	No	Age (days)	Mass (Kg)	Failure load (kN)	Density (Kg/m^3)	Split tensile strength (MPa)	Mean split tensile strength (MPa)
	1	14	3.4550	29.1	2368.9	1.3	1.3
	2		3.4605	33.2	2372.7	1.4	
	3		3.4625	37.1	2374.1	1.6	
	1	28	3.4715	38.9	2380.3	1.7	1.8
	2		3.4750	42.4	2382.7	1.8	
	3		3.4770	42.9	2384.1	1.9	
	4		3.4730	41.8	2381.3	1.8	

Table 10.115: Ratio between compressive to split tensile strength at 28 days

Mix code	Compressive strength (MPa)	Split tensile strength (MPa)	Ratio between compressive to split tensile strength	Average of the ratios
Best mix (OPC7/GGBS6.3/BPD0.7)	20.3	3.6	5.6	5.9
Best mix with 6 & 4mm IBAA replacement	13.6	1.9	7.2	
Best mix with 4mm IBAA replacement	12.7	2.3	5.5	
Best mix with 6 mm IBAA replacement	16.6	3.2	5.2	
Best mix with 6 mm RCA type I replacement	16.9	3.3	5.1	
Best mix with 6 mm RCA type II replacement	15.8	3.2	4.9	
Best mix with 4 mm RCG replacement	9.5	2.2	4.3	
Best mix with 6 mm RB replacement	15.9	3.1	5.1	
Best mix with 1.5 % steel fibre	17.7	3.6	4.9	
Best mix with 6 PVA	19.1	2.0	9.5	
Best mix with 10 PVA	14.4	1.8	8.0	

Table 10.116: Comparing the split tensile strength results of paving blocks between Aggregate Industries factory and Coventry university lap

Blocks No.	Split tensile strength (MPa) (results from the factory)			Split tensile strength (MPa) (results from Coventry university lap)		
	7 (days)	14 (days)	28 (days)	7 (days)	14 (days)	28 (days)
B2	2.6			2.3		
B3	2.9			2.4		
B4	2.8			2.4		
B5	2.7			2.5		
B6	2.8			2.2		
B7	2.8					2.3
B8			3.7			2.8
B9			3.7			2.9
B10			3.4			2.9
B11			3.6			2.9
C2					2.3	
C3					2.3	
C4					2.4	
C5					2.3	
C6					2.6	
C7						2.4
C8			3.8			2.5
C9			3.8			2.8
C10						2.7

Table 10.117: Comparing the split tensile strength results of paving blocks between Formpave factory and Coventry university lap

Blocks No.	Split tensile strength (MPa) (results from the factory)			Split tensile strength (MPa) (results from Coventry university lap)		
	7 (days)	14 (days)	28 (days)	7 (days)	14 (days)	28 (days)
A1	3.1			2.3		
A2	2.6			2.3		
A3	3.0			2.5		
A4		3.2			2.9	
B1		3.4			2.8	
B2		3.7			3.3	
B3			3.9			3.2
B4			3.5			3.2
B5			3.6			3.2

Table 10.118: Mixture design and split tensile strength for OPC-ROSA-PG at 14 days for concrete paving block tested at different conditions

Mix code		OPC52/ROSA30/BOS18				
Cement		ROSA	BOS	4mm-Dust	6mm Clean	Sand
7.3%		4.2%	2.5%	53%	9%	24%
Blocks	Blocks under different condition		Failure load (kN)		Split tensile strength (MPa)	
	Block at ambient condition		60.92		2.6	
	Block after oven dry condition		71.35		3.1	
	Block at saturated condition		35.42		1.5	

Table 10.119: Mixture design and split tensile strength for OPC-ROSA-PG at 14 days for binder paving block tested at saturated condition

Mix code		Failure load (kN)	Split tensile strength (MPa)	Average split tensile strength (MPa)
OPC80/ROSA15/PG5				
OPC	80%	51.80	2.24	2.22
ROSA	15%	50.23	2.17	
PG	5%	51.73	2.24	

10.6: XRD results for all mixes.

The results of the XRD test of all mixes are shown in Figures 10.21 to10.30.

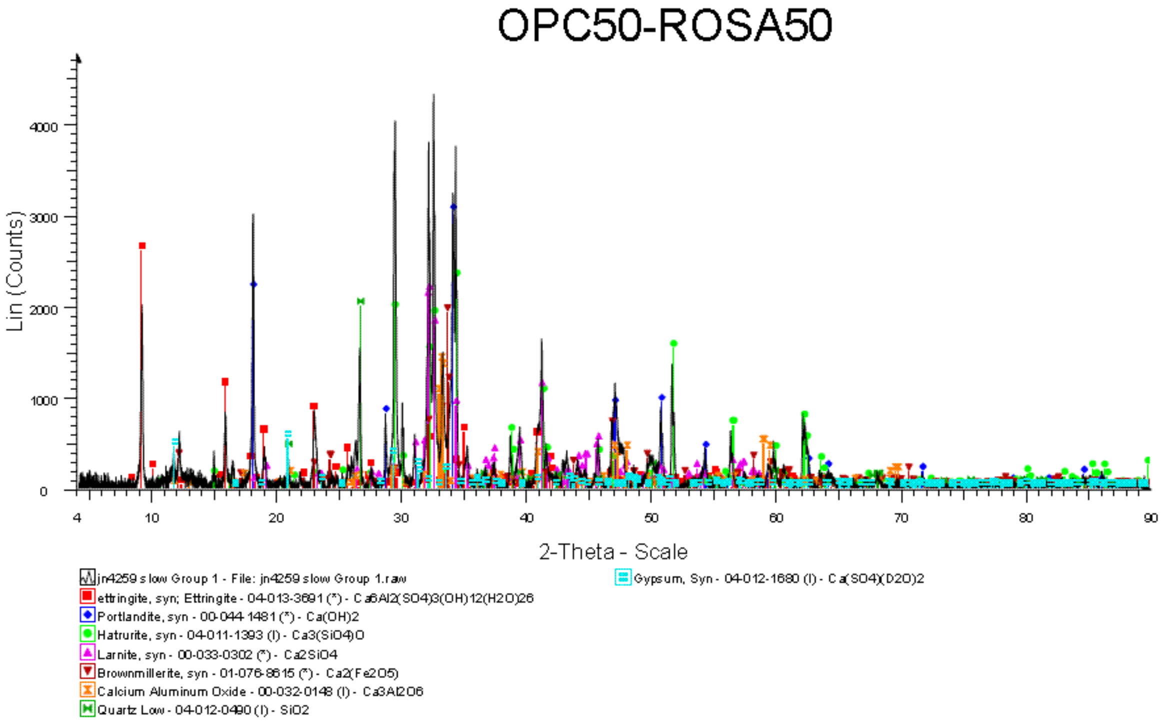

Figure 10.21: XRD test of OPC50-ROSA50 mix at 28 days

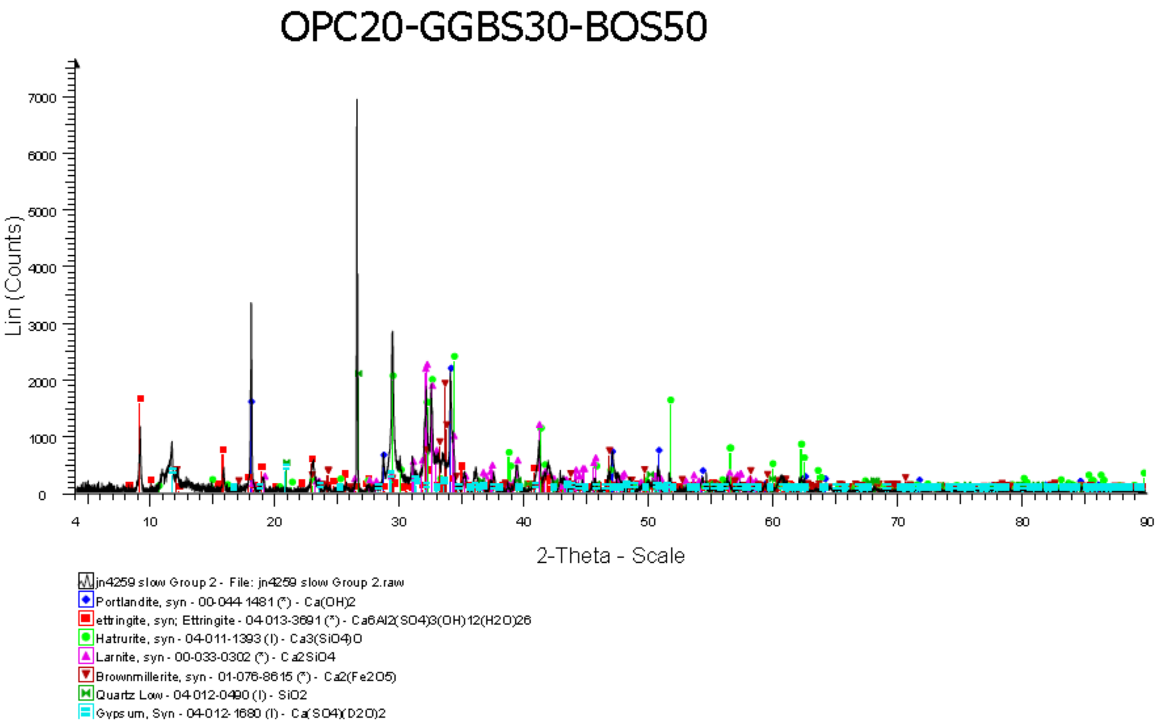

Figure 10.22: XRD test of OPC20-GGBS30-BOS50 mix at 28 days

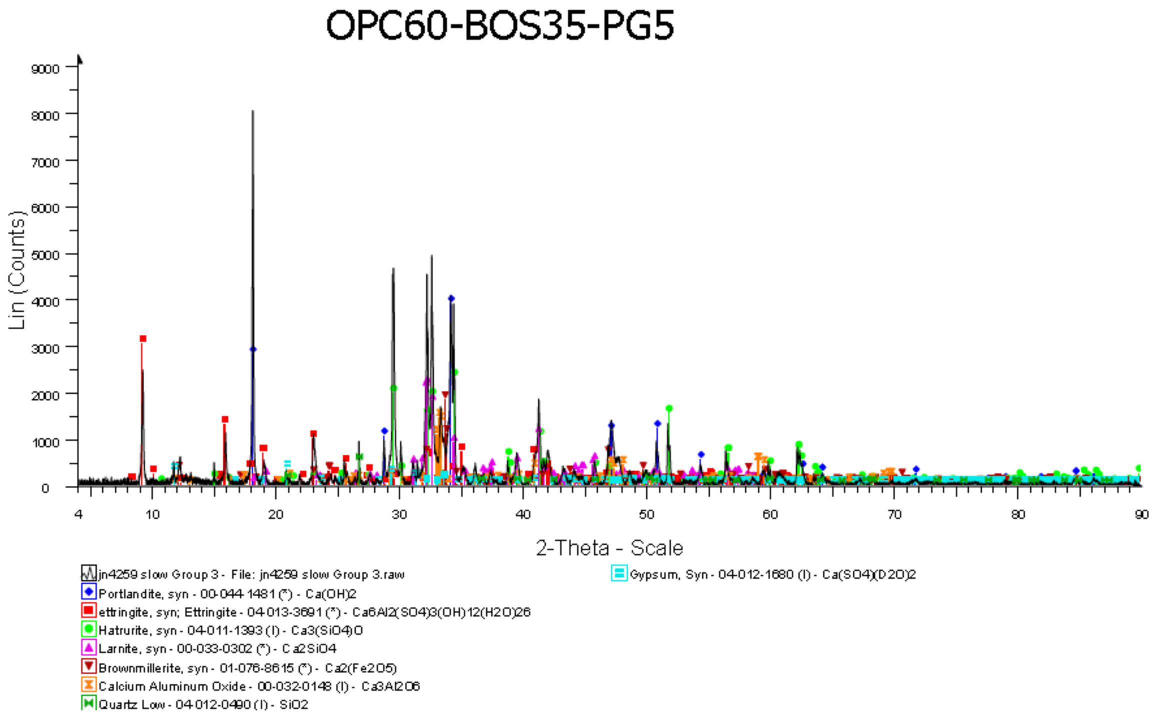

Figure 10.23: XRD test of OPC50-BOS35-PG5 mix at 28 days

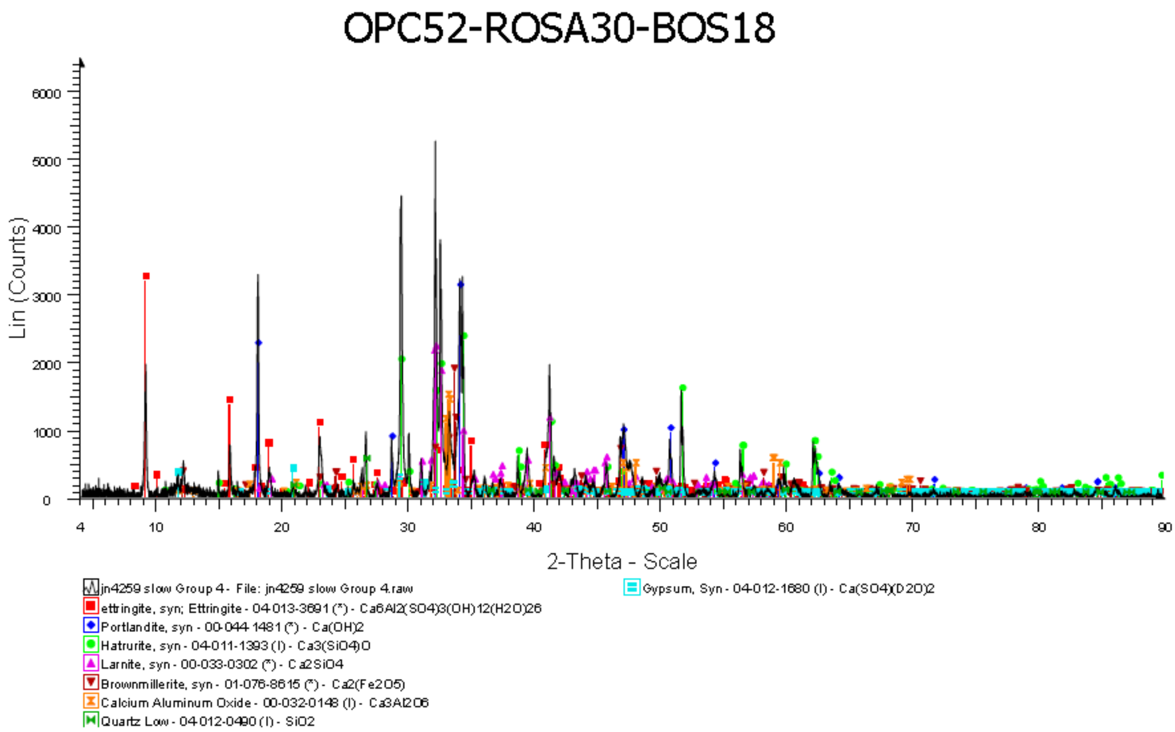

Figure 10.24: XRD test of OPC52-ROSA30-BOS18 mix at 28 days

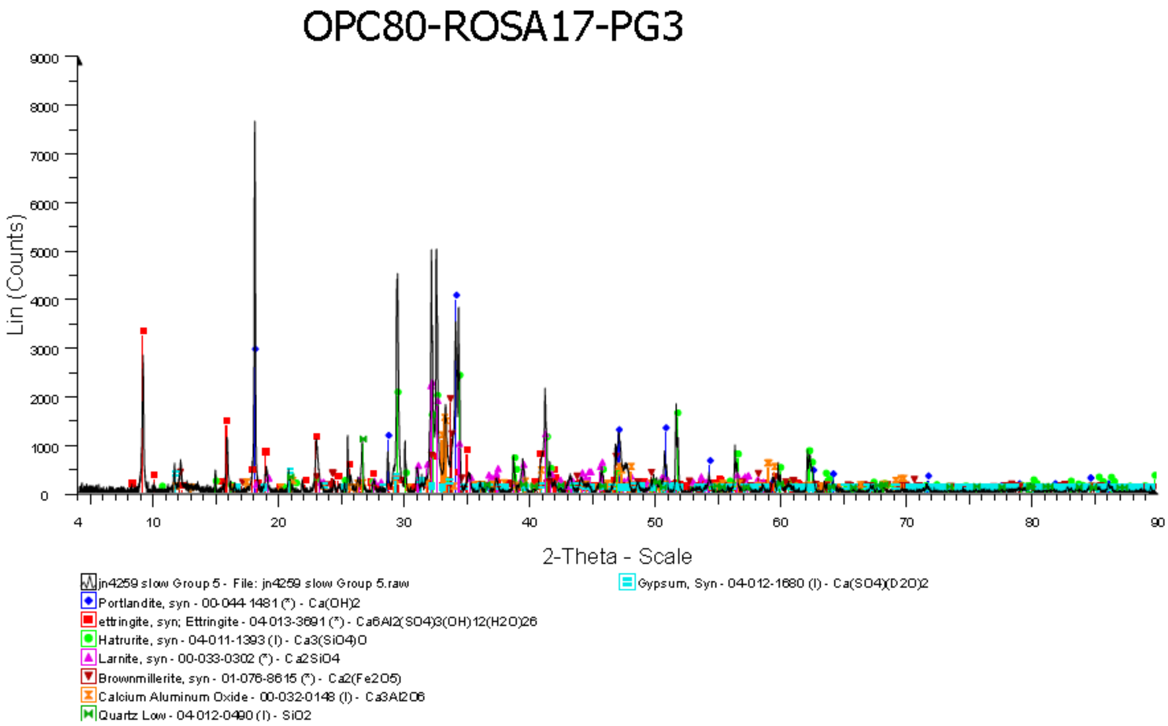

Figure 10.25: XRD test of OPC80-ROSA17-PG3 mix at 28 days

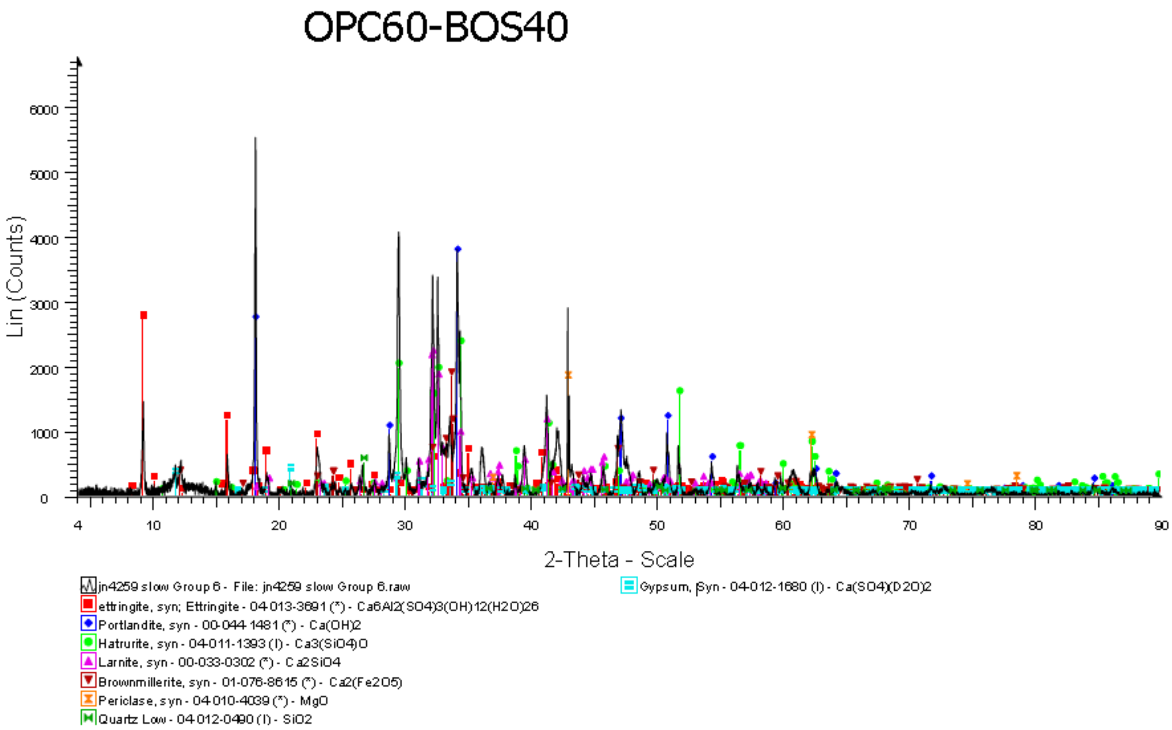

Figure 10.26: XRD test of OPC60-BOS40 mix at 28 days

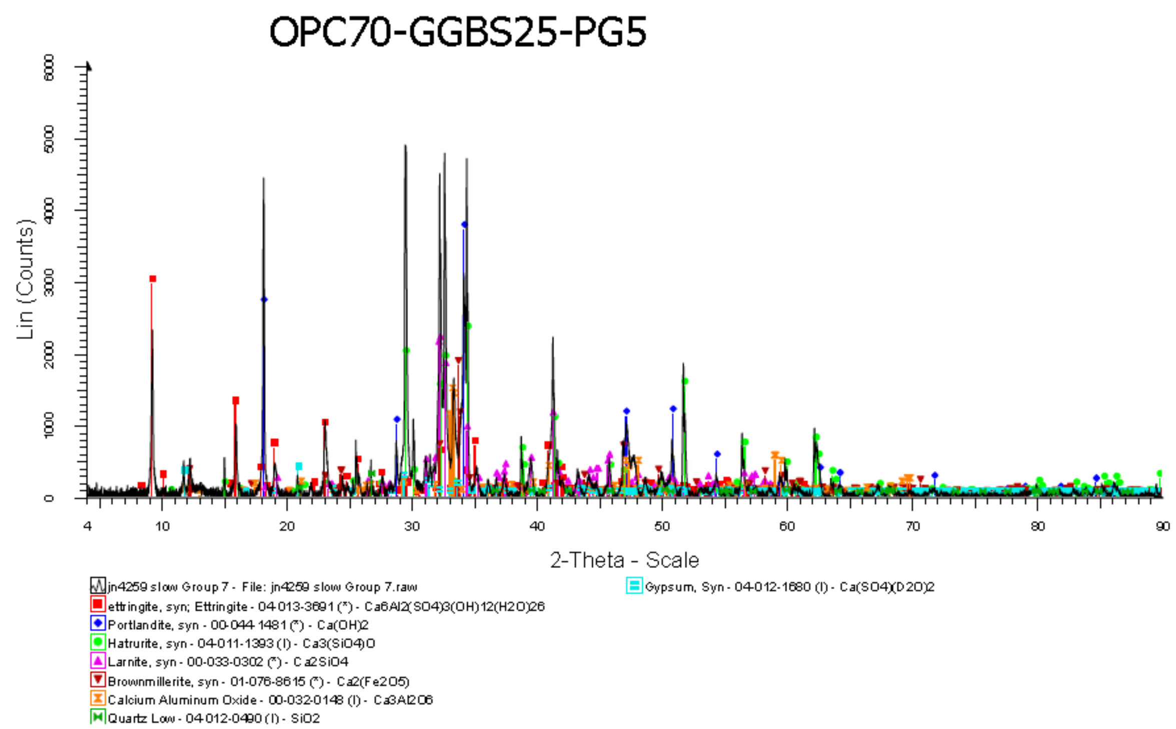

Figure 10.27: XRD test of OPC70-GGBS25-PG5 mix at 28 days

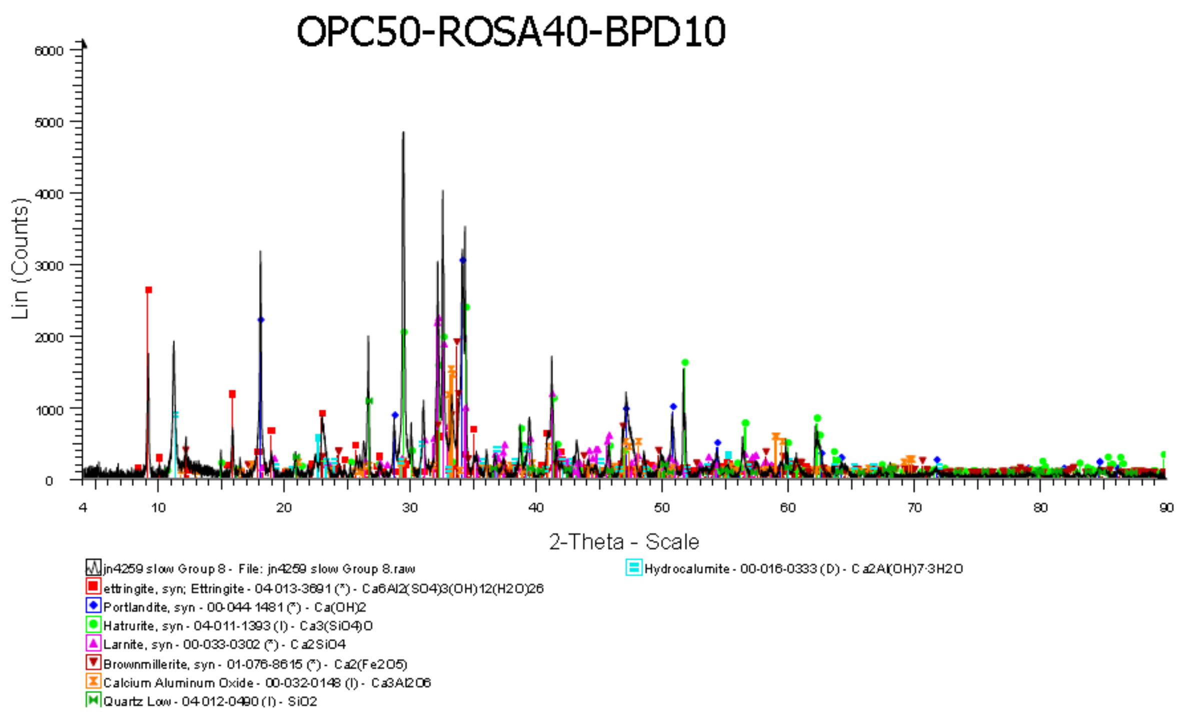

Figure 10.28: XRD test of OPC50-ROSA40-BPD10 mix at 28 days

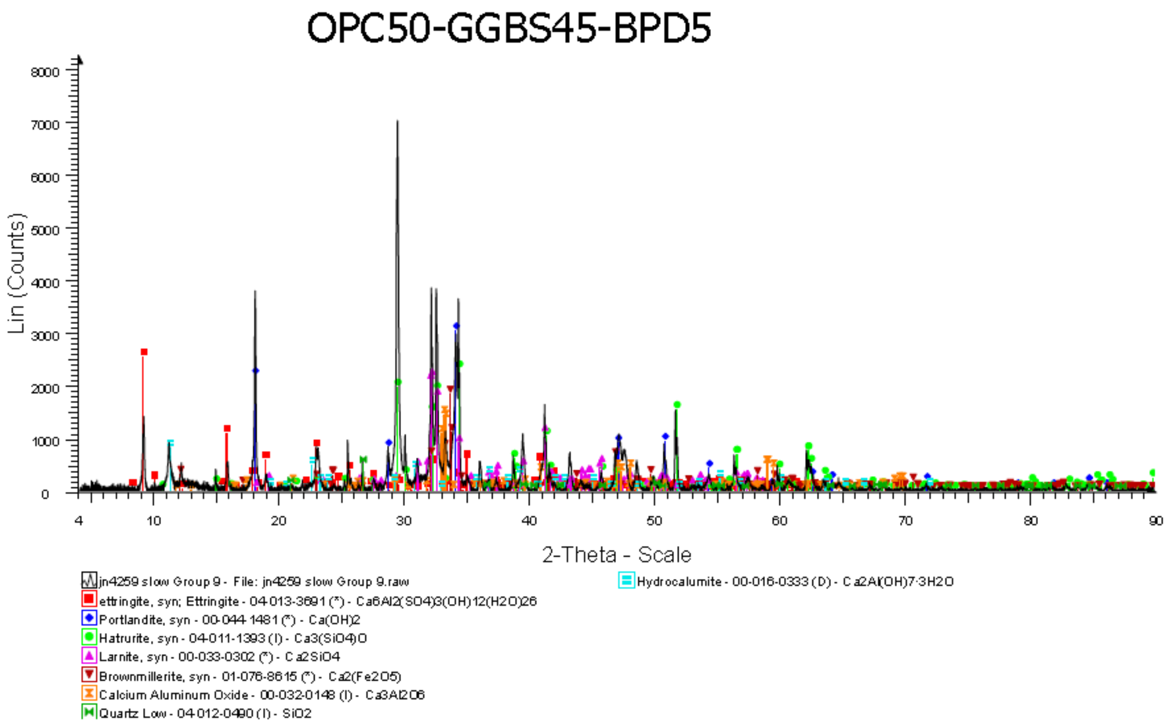

Figure 10.29: XRD test of OPC50-GGBS45-BPD5 mix at 28 days

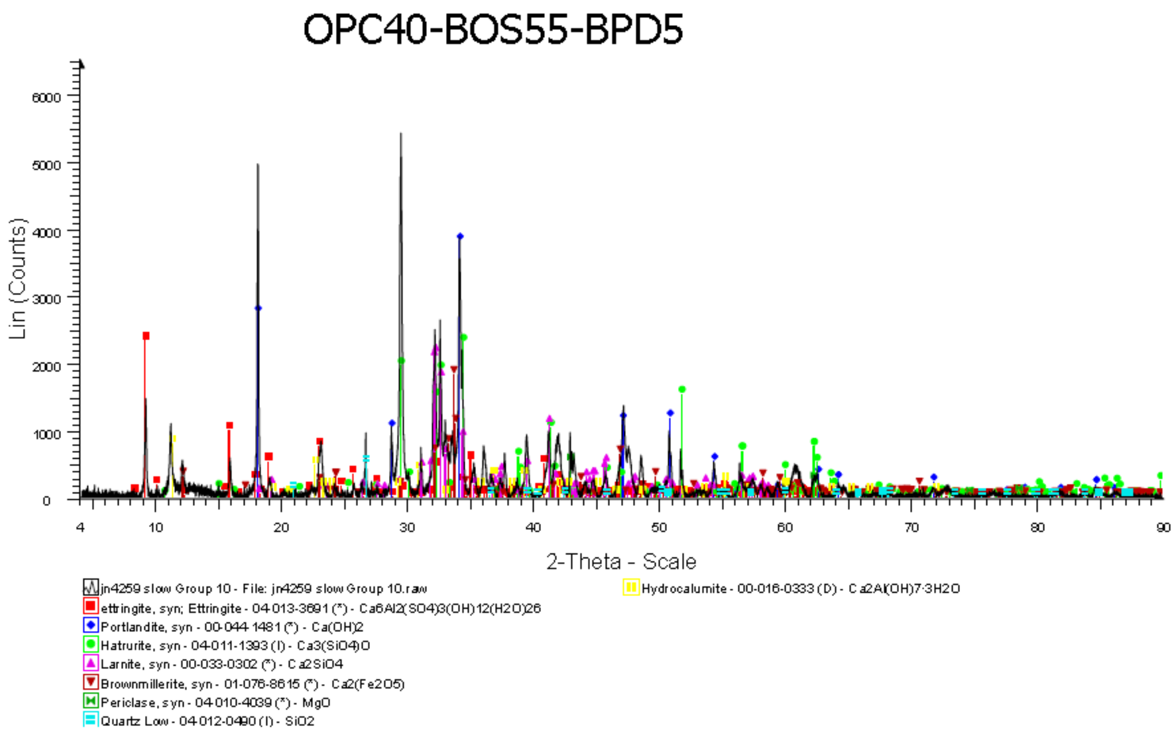

Figure 10.30: XRD test of OPC40-BOS55-BPD5 mix at 28 days